Project 001(F) Alternative Jet Fuel Supply Chain Analysis

Massachusetts Institute of Technology

Project Lead Investigator

PI: Steven R. H. Barrett
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. Raymond L. Speth
Principal Research Scientist
Laboratory for Aviation and the Environment
Massachusetts Institute of Technology
77 Massachusetts Ave, Building 33-322, Cambridge, MA 02139
+1 (617) 253-1516
speth@mit.edu

Co-PI: Dr. Florian Allroggen
Research Scientist
Laboratory for Aviation and the Environment
Massachusetts Institute of Technology
77 Massachusetts Ave, Building 33-115A, Cambridge, MA 02139
+1 (617) 715-4472
fallrogg@mit.edu

University Participants

Massachusetts Institute of Technology (MIT)

- PI: Professor Steven R. H. Barrett
- FAA Award Number: 13-C-AJFE-MIT, Amendment Nos. 003, 012, 016, 028, 033, 040, 048, 055, 058, 067, 082, and 088
- Period of Performance: August 1, 2014 to September 30, 2022
- Tasks (those listed here are for the reporting period September 1, 2020 to August 30, 2021):
    1. Support U.S. participation in the International Civil Aviation Organization Committee on Aviation Environmental Protection (ICAO CAEP) to enable appropriate crediting of the use of sustainable aviation fuels (SAF) under the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA).
    2. Support U.S. participation in the ICAO CAEP by performing core life cycle analysis (CLCA) to establish default values for use under CORSIA.
    3. Contribute to the development of the fuel production assessment for CORSIA-eligible fuels, especially as it relates to fuels produced from waste CO_2 and atmospheric CO_2.
    4. Develop methods for probabilistic life-cycle analyses and techno-economic analyses in the context of assessing U.S.-based SAF production until 2035.
    5. Support knowledge-sharing and coordination across all ASCENT Project 01 universities working on SAF supply-chain analyses.

Hasselt University (UHasselt, through subaward from MIT)

- PI: Robert Malina
- Period of Performance: September 1, 2016 to August 31, 2022

- Tasks (those listed below are for the reporting period September 1, 2020 to August 30, 2021):
    1. Support and provide leadership for U.S. participation in the ICAO CAEP to enable appropriate crediting of the use of SAF under CORSIA, especially as it relates to feedstock classification and pathway definitions.
    2. Support U.S. participation in ICAO CAEP by carrying out CLCA to establish default values for use under CORSIA.
    3. Contribute to the development of the fuel production assessment for CORSIA-eligible fuels out to the year 2035
    4. *Omitted; Task led by MIT.*
    5. *Omitted; Task led by MIT.*

Project Funding Level

$3,585,000 FAA funding and $3,585,000 matching funds. Sources of matching funds include approximately $546,000 from MIT as well as third-party in-kind contributions of $809,000 from Byogy Renewables, Inc.; $1,038,000 from Oliver Wyman Group; and $791,000 from NuFuels LLC; and $401,000 from Savion Aerospace Corp.

Investigation Team

Principal Investigator:	Prof. Steven Barrett (MIT) (all MIT tasks)
Principal Investigator (UHasselt Subaward):	Prof. Robert Malina (UHasselt) (all UHasselt tasks)
Co-Principal Investigator:	Dr. Florian Allroggen (MIT) (all MIT tasks)
	Dr. Raymond Speth (MIT) (Task 4)
Postdoctoral Associates:	Christoph Falter (MIT) (Tasks 1, 2 and 3)
	Freddy Navarro Pineda (UHasselt) (all UHasselt tasks)
	Gonca Seber (UHasselt) (Task 2)
	Parisa Raffiani (UHasselt) (Task 2)
	Katrijn Gijbel (UHasselt) (Task 2)
Research Specialist:	Matthew Pearlson (MIT) (Tasks 2 and 4)
	Charlotte Adrianssen (UHasselt) (Task 3)
Graduate Research Assistants:	Tae Joong Park (MIT) (Task 1and 2)
	Walter Kelso (MIT) (Tasks 1 and 4)
	Iias Mokas (UHasselt) (Task 3)

Project Overview

The overall objectives of ASCENT Project 01 (A01) are to (i) derive information on regional supply chains to explore scenarios for future sustainable aviation fuel (SAF) production and (ii) identify supply chain-related obstacles to commercial-scale production in the near term and larger-scale adoption in the longer term.

For the assessment year (AY) 2020/21, the MIT/UHasselt team contributed to these goals by: (1) providing leadership in the International Civil Aviation Organization Committee for Aviation Environmental Protection (ICAO CAEP) core life cycle analysis (CLCA) task group of the Fuels Task Group (FTG), which is mandated to calculate lifecycle greenhouse gas (GHG) emissions associated with the use of SAF; (2) performing CLCA to enable the inclusion of additional SAF pathways under CORSIA or verify CLCA values calculated by other institutions; (3) contributing to the analysis of SAF availability in 2050; (4) analyzing the availability of U.S.-produced SAFs in 2035 and their associated lifecycle emissions and costs using a stochastic model; and (5) contributing to knowledge transfer in the ASCENT 01 team.

Task 1 – Support and provide leadership for U.S. participation in ICAO CAEP to enable appropriate crediting of the use of SAF under CORSIA, especially as it relates to feedstock classification and pathway definitions.

Massachusetts Institute of Technology
Hasselt University

Objectives

The overall objective of this task is to provide leadership for and support to the FAA in their engagement with the ICAO CAEP FTG (during CAEP/12). The specific focus of the work during this reporting period was to (1) refine pathway definitions; (2) support discussions toward the development of a CLCA method for lower-carbon aviation fuels (LCAF); and (3) provide guidance on the inclusion of Power-to-Liquid (PtL) fuels.

Research Approach

To achieve the goals outlined above, the team continued to co-lead the CLCA Task Group of FTG. Prof. Malina acted as a co-lead. This role ensures that Prof. Malina remains a focal point of CLCA research, so that specific research tasks can be guided efficiently and effectively. The following research has been conducted in support of the leadership role:

Pathway definitions

Under the leadership of the CLCA task lead, Professor Malina, we reviewed the assumptions made in the development of default CLCA values. This review aimed to understand if Sustainable Certification Schemes (SCS) require additional guidance on the applicability of a certain default value. The results of this assessment were discussed at the FTG/6 meeting, and definitions will be brought forward at the CAEP/13 meeting. These definitions pertain to sustainable residue removal rates, standalone vs. integrated conversion designs for alcohol-to-jet (ATJ) pathways, and closed-pond palm oil hydroprocessed esters and fatty acids (HEFA) systems.

Leadership for the development of the LCAF methods

The MIT and UHasselt team were actively involved in the development of a draft methodology for including LCAF in the CORSIA package via both quantitative analysis and regulatory proposals. This draft methodology addresses both LCAF eligibility considerations as well as LCAF crediting considerations.

Guidance on including Power-to-Liquid (PtL) Fuels

During FTG/08, the CLCA subgroup was tasked to begin working on CLCA values for SAF produced through PtL pathways. The MIT team led the development of a coherent definition of PtL pathways. MIT proposed creating this definition based on a classification of SAF pathways, which relies on their (1) hydrogen source, (2) carbon source, and (3) conversion process. PtL fuels are fuels which rely on electricity as a main input to produce hydrogen and, potentially, carbon. PtL pathways include, but are not limited to, Fischer-Tropsch pathways that leverage low-carbon hydrogen sources and either waste CO_2 or direct air capture. Non-traditional PtL pathways, such as gas fermentation to ethanol followed by ATJ, could use low-carbon hydrogen and carbon-containing feedstock derived similarly to other PtL pathways.

Given the broad range of potential PtL pathways, MIT and other FTG experts recommended including PtL pathways through actual values while the most practical pathways are still emerging.

Milestones

The work described above has been documented in numerous Working Papers and Information Papers submitted to FTG. UHasselt and MIT experts participated in and contributed to numerous FTG meetings, including FTG/06 (November 2020), FTG/07 (February 2021), FTG/08 (March 2021), FTG/09 (May 2021), and FTG/10 (July 2021).

Major Accomplishments

The MIT and UHasselt team accomplished the following under this task:

1. As co-lead of the FTG-CLCA Task Group, Prof. Malina drafted CLCA progress reports to FTG meetings, where CLCA topics were discussed during the current reporting period. In addition, Prof. Malina co-led several Task Group meetings.
2. The MIT team led the development of the definition of PtL pathways for consideration under CORSIA.

Publications

CAEP/12-FTG/06-WP/02. Summary of the progress of the CLCA Subgroup since FTG/03. November 2020.
CAEP/12-FTG/08-WP/04. Summary of the progress of the CLCA Subgroup since FTG/07. March 2021.
CAEP/12-FTG/10-WP/03. Summary of the progress of the CLCA Subgroup since FTG/09. July 2021.
CAEP/12-FTG/10-IP02: Life cycle analysis methodology for lower carbon aviation fuels
CAEP/12-FTG/10-IP/03: Option for Addressing Eligibility and Crediting of LCAF in CORSIA Life Cycle Analysis Framework

Zhao, X., Taheripour, F., Malina, R., Staples, M. D., & Tyner, W. E. (2021). Estimating induced land use change emissions for sustainable aviation biofuel pathways. Science of the Total Environment, *779*, 146238.

Outreach Efforts

Progress on these tasks was communicated during weekly briefing calls with the FAA and other U.S. delegation members to FTG, as well as during numerous FTG teleconferences between meetings. In addition, UHasselt and MIT experts participated in and contributed to numerous FTG meetings, including FTG/06 (November 2020), FTG/07 (February 2021), FTG/08 (March 2021), FTG/09 (May 2021), and FTG/10 (July 2021).

Awards

None.

Student Involvement

During this reporting period, the MIT graduate student involved in this task was TJ Park, who received his S.M. degree in the summer of 2021.

Plans for Next Period

In the coming year, the MIT ASCENT Project 01 team will continue its work in FTG. Default core LCA values will be calculated and proposed for additional pathways, and Prof. Malina will continue to lead the core LCA Task Group. A particular focus will be to shape the agenda for the CAEP/13 cycle.

Task 2 – Support U.S. Participation in ICAO CAEP by Performing CLCA to Establish Default Values for Use Under CORSIA

Massachusetts Institute of Technology
Hasselt University

Objective

During the CAEP/11 cycle, the MIT ASCENT Project 1 team took leadership in applying the agreed-upon CLCA method to establish default CLCA values for 26 unique pathways. However, the list of 26 pathways is not exhaustive, and further CLCA analysis is required to enable inclusion of SAF technologies that are nearing commercialization. During the current reporting period, the team supported (1) the calculation of default CLCA values for fuels produced from co-processing biogenic and fossil feedstocks in conventional refineries; (2) the calculation of default CLCA values for the Jatropha HEFA pathway; and (3) the verification of the waste gas ethanol-to-jet pathway using updated ethanol-to-jet life-cycle inventories.

Research Approach

Co-processing

Co-processed fuels are produced by upgrading biogenic feedstocks to jet fuel alongside petroleum feedstock in existing refineries. In their current specification (ASTM D1655-20, A.1.2.2 [ASTM International, 2020]), ASTM allows co-processed jet fuels to be produced by co-processing monoglycerides, diglycerides, triglycerides, free fatty acids, and fatty acid esters as biogenic feedstocks at up to 5% inputs by volume through either hydrocracking or hydrotreating and fractionation. For our initial analyses, we limited the scope of the pathways we investigated to hydroprocessing via either a hydrotreater or hydrocracker, depending on the biogenic feedstocks and petroleum-derived distillates used. Figure 1 shows a simplified refinery configuration example using middle distillates and a hydrotreater.

The initial list of feedstocks (Table 1) follows the HEFA SAF feedstocks for which CLCA values have been published (ICAO, 2019). Co-processing is not limited to these feedstocks, and the analysis can be expanded to include other feedstocks.

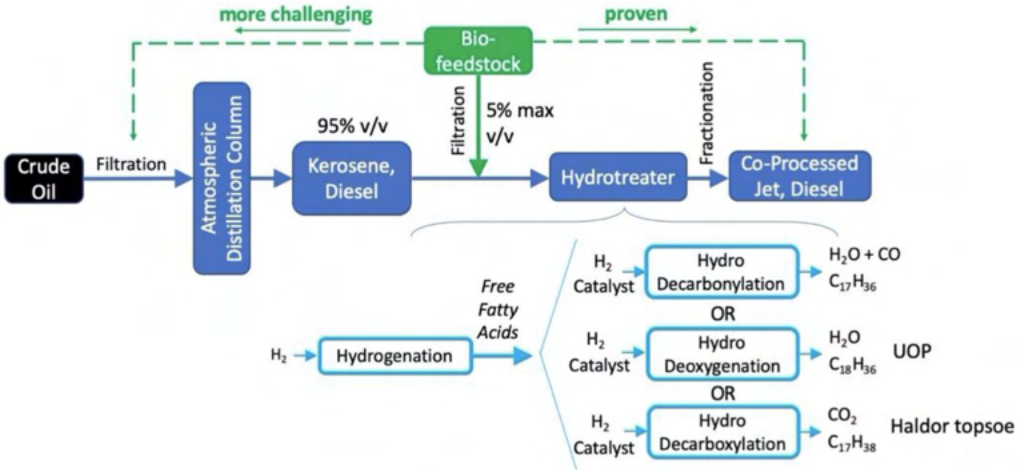


Figure 1. Illustration of co-processing of HEFA bio-feedstock with middle distillates.

Table 1. List of HEFA feedstocks to be considered for co-processing.

Feedstock	Type	Details
Used cooking oil (UCO)	Waste	Cooked vegetable oil
Tallow	By-product	Fats from cattle slaughtering
Palm fatty acid distillate		Stripped from crude palm oil during refined palm oil production
Corn oil		Extracted from distillers dry grains/solubles
Oil crops	Main	Soybean, canola/rapeseed, camelina
Palm oil		Closed (w/methane capture) or open pond (w/o methane capture)
Brassica carinata		Primary summer crop in U.S./Canada

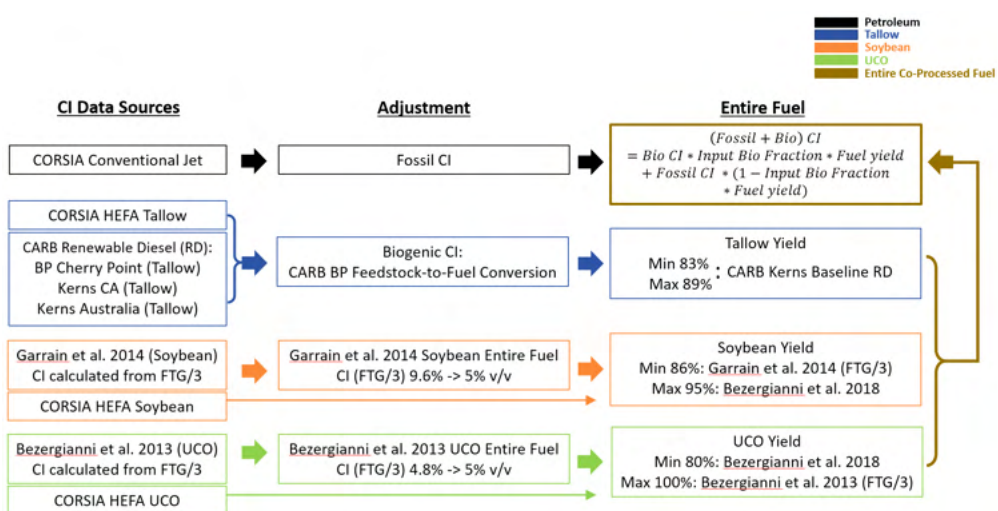


Figure 2. Data sources and adjustments made for carbon intensity (CI) calculation.

For the LCA, the MIT team used a top-down approach that incorporates values from the literature into each step of the well-to-tank LCA and considers three biogenic feedstocks: tallow, used cooking oil (UCO), and soybean oil. The purpose of the top-down approach was to validate the results from the bottom-up LCA led by the Argonne National Laboratory (ANL). Figure 3 shows results of the top-down approach for the biogenic portion of the fuel using adapted data from the academic literature (Garrain et al. [2014], Bezergianni et al. [2013]) and public industry data from renewable diesel production at the refineries in Cherry Point, WA (CARB, 2019) and Kerns in Bakersfield, CA (CARB, 2020). The ranges we obtained generally agreed with the LCA results from the bottom-up approach.

In addition, the MIT team participated in discussions led by the Argonne National Laboratory to perform linear programming modeling of a refinery with and without co-processing, including feedstock choice, feedstock chemical characterization, refinery configuration, and case combination selection. The MIT team also contributed to the marginal allocation method that was ultimately used for the bottom-up approach.

Finally, MIT contributed to the development of the equations to be used for calculating the CI of the entire co-processed fuel, including the petroleum-derived portion, to be considered under CORSIA.

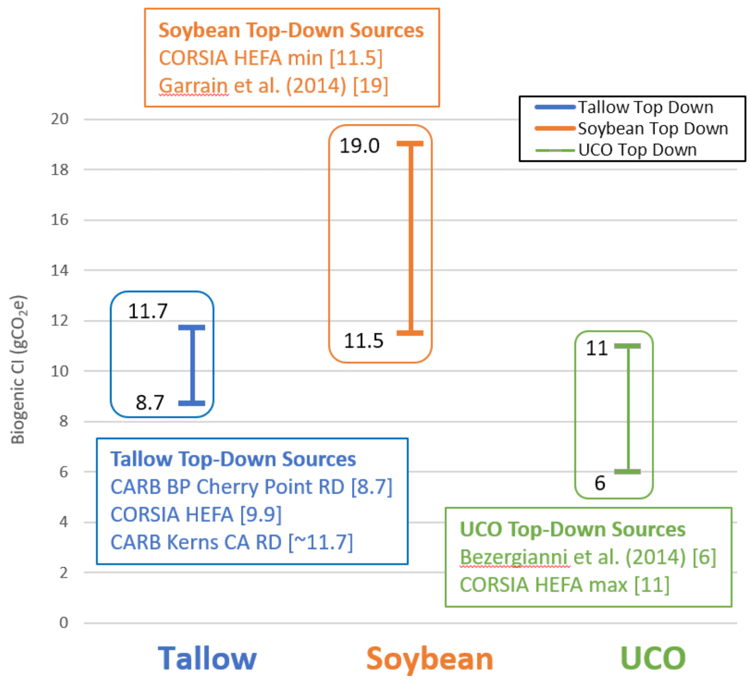


Figure 3. Top-down LCA ranges.

Jatropha HEFA pathway

UHasselt and JRC independently modeled Jatropha-HEFA, in line with the other oilseed-HEFA pathways, and the results were presented at FTG/06. The co-products of the oil extraction process from jatropha are meal, husk, and shell. However, jatropha meal is toxic and therefore cannot be used as fodder unless it is detoxified. During the FTG/06 meeting, experts suggested the development of different pathway values as a function of the meal use and the use of husk and shell as additional co-products. The UHasselt team performed an extensive literature review on jatropha and identified the most likely pathways for oil extraction by-products (see Figure 4). The team then calculated a set of GHG emission values for different scenarios and presented the work to FTG/08. Three different pathways were analyzed, in which it was assumed that jatropha meal could be used as fertilizer, fodder (after detoxification), or combusted for electricity production. All scenarios assumed that the shells and the husks from the process were combusted for electricity generation.

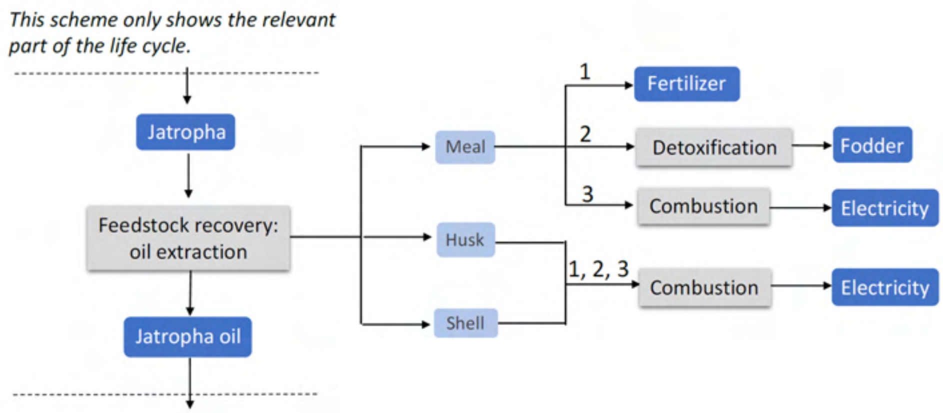


Figure 4. Analyzed pathways for jatropha co-products.

The U.S. and India were considered as world regions for the analysis, and regional electricity mixes were used for each country. UHasselt calculated the CLCA values using the Greenhouse Gases, Regulated Emissions, and Energy Uses in Technologies (GREET) model, and the Argonne National Laboratory verified the calculations. CLCA values for these scenarios ranged between 42.1 and 50.1 gCO_2e/MJ (see Table 1). These values are within the 8.9 gCO2e/MJ envelope that can constitute a fuel production pathway within CORSIA.

Table 1. CLCA values for different scenarios of the jatropha HEFA pathway (in gCO_2e/MJ).

Scenario	Region	Feedstock cultivation	Feedstock transportation	Oil extraction	Oil transportation	Jet fuel production	Jet fuel transportation	Total emissions	Midpoint value
1	US	24.9	0.71	3.66	0.38	12.1	0.37	42.1	**46.0**
	India	25.9	0.72	3.67	0.38	12.5	0.38	43.6	
2	US	27.3	0.78	4.26	0.38	12.1	0.37	45.2	
	India	28.4	0.79	4.29	0.38	12.5	0.38	46.8	
3	US	29.8	0.85	4.87	0.38	12.1	0.37	48.3	
	India	31.0	0.86	4.88	0.38	12.5	0.38	50.1	

CLCA Validation and verification
The UHasselt team served as the verifier for lifecycle analysis on the integrated and standalone waste gas ethanol-to-jet pathway.

Milestones

The work described above has been documented in numerous Working Papers and Information Papers submitted to the FTG. UHasselt and MIT experts participated in and contributed to numerous FTG meetings, including FTG/06 (November 2020), FTG/08 (March 2021), FTG/09 (May 2021), and FTG/10 (July 2021), where these topics were discussed.

Major Accomplishments

The MIT and UHasselt team accomplished the following under this task:

1. The team contributed to analyses and methods that established a default CLCA value for co-processed fuels and provided guidance for calculating actual CLCA values for co-processed fuels.
2. The team provided detailed analyses on the CLCA value for the Jatropha HEFA pathway, which informed discussions within FTG and lead to the approval of default jatropha CLCA default values.
3. The team acted as verifier to the integrated and standalone waste gas to ethanol pathway that led to the approval of default CLCA values for these pathways.

Publications

CAEP/12-FTG/06-WP/02. Summary of the progress of the CLCA Subgroup since FTG/03. November 2020.

CAEP/12-FTG/06-WP/03. Default values for jatropha to HEFA pathways. November 2020.
CAEP/12-FTG/06-IP/04. Summary of progress since FTG/05 on calculating LCA values for fuels produced through co-processing of biogenic feedstock with petroleum feedstock. November 2020.
CAEP/12-FTG/06-FL/02. Proposed Jatropha Assessment Cases. November 2020.
CAEP/12-FTG/08-WP/04. Summary of the progress of the CLCA Subgroup since FTG/07. March 2021.
CAEP/12-FTG/09-WP/04. Life-cycle analysis of co-processed sustainable aviation fuels. May 2021.
CAEP/12-FTG/10-WP/03. Summary of the progress of the CLCA Subgroup since FTG/09. July 2021.

Outreach Efforts

Progress on these tasks was communicated during weekly briefing calls with the FAA and other U.S. delegation members to FTG, as well as during numerous FTG teleconferences between meetings. In addition, UHasselt and MIT experts participated in and contributed to numerous FTG meetings, including FTG/06 (November 2020), FTG/07 (February 2021), FTG/08 (March 2021), FTG/09 (May 2021), and FTG/10 (July 2021).

Awards

None

Student Involvement

TJ Park, Master's degree student at MIT, contributed to the analysis on co-processing.

Plans for Next Period

The team will continue to perform attributional CLCA to establish default values for use under CORSIA. More specifically, the team expects to support efforts to determine CLCA values for co-processed fuels and novel fuel pathways (e.g., catalytic thermolysis), as well as establish additional default CLCA values for pathways such as jatropha HEFA.

References

ASTM International. (2020). Standard specification for aviation turbine fuels (Report No. D1655-20). ASTM International, West Conshohocken, PA. https://doi.org/10.1520/D1655-20

Bezergianni, S., & Dimitriadis, A. (2013). Temperature effect on co-hydroprocessing of heavy gas oil-waste cooking oil mixtures for hybrid diesel production. Fuel *103*, 579–84.

CARB. (2020). California LCFS Tier 2 fuel pathway application: GREET Pathway for the Production of Renewable Diesel from Animal Tallow. (GREET modelling technical support document). CARB, Sacramento, CA, https://ww2.arb.ca.gov/sites/default/files/classic/fuels/lcfs/fuelpathways/comments/tier2/b0079_report.pdf

CARB. (2019). California LCFS Tier 2 fuel pathway application: Renewable diesel produced from co-processed animal fat at the BP Products North America Inc Cherry Point Refinery using natural gas, steam, and electricity as process energy (GREET modelling technical support document). CARB, Sacramento, CA. Retrieved from ww3.arb.ca.gov/sites/default/files/classic/ fuels/lcfs/fuelpathways/comments/tier2/b0018_report.pdf

Garrain, D., Herrara, I., Lechon, Y., & Lago, C. (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*, 239-249.

ICAO., (2019). CORSIA Eligible Fuels – Life Cycle Assessment Methodology (CORSIA supporting document). ICAO, Montreal, Canada. Retrieved from https://www.icao.int/environmentalprotection/CORSIA/Documents/CORSIA%20Supporting%20Document_CORSIA%20Eligible%20Fuels_LCA%20Methodology.pdf

Task 3 – Contribute to the Development of the Fuel Production Assessment for CORSIA-eligible Fuels

Hasselt University
Massachusetts Institute of Technology

Objective

The UHasselt team aimed to contribute to the development of the fuel production assessment for CORSIA-eligible fuels out to the year 2035. The results of this will then be extrapolated to 2050 and fed into the CAEP Modelling and Databases

Group (MDG) process. During the reporting period, this work was accelerated and re-scoped to inform efforts under ICAO's Long-Term Aspiration Goals (LTAG) Task. The research was completed jointly with researchers from Washington State University and Purdue University.

In addition, the MIT team analyzed potential availability scenarios for fuels leveraging either waste CO_2 sources or atmospheric CO_2 sources, using pathway modeling completed under ASCENT Project 52 as well as data from future hydrogen production scenarios, grid scenarios, and sectoral CO_2 emission projections. The research was completed jointly with researchers from the Argonne National Laboratory.

Research Approach

Fuel production assessment for CORSIA eligible fuels

A short-term projection database on proposed SAF production was generated. This database includes data and references from publicly available production announcements from companies planning to make SAF over the next five years. It only tallies potential SAF production, not LCAF. Using this database, and a set of criteria and assumptions, we modeled a short-term SAF production ramp-up under five production scenarios (low, moderate, high, high+, and max). These scenarios differed with respect to the type of companies included, the maturity of the production plans, and the assumptions concerning product slate and the success rate of announced production plans (see Tables 2 and 3). The resulting ramp-ups from each scenario were then taken as a starting point to forecast SAF production out to 2035 assuming a diffusional approach that will be extended out to 2050.

Table 2. Definition of the short-term SAF production scenarios.

Scenario	Code[a]	Maturity[a]	Facility Jet Fuel Ratio	Overall Success Rate for A Maturity	Overall Success Rate for B Maturity	Overall Success Rate for C Maturity
Low	1	A, B	Actual or low %	25%	10%	0%
Moderate	1-2	A, B, C	Actual or low %	50%	25%	10%
High	1-3	A, B, C	Actual or high% for codes 1-2, Actual or low% for code 3	75%	50%	25%
High+	1-3	A, B, C	High%	75%	50%	25%
Max	1-3	A, B, C	High%	100%	100%	100%

[a] See Table 3.

Figure 5 shows the SAF production estimates derived from the short-term projection database and the developed scenarios, as well as the fit considering the diffusional approach. Figure 6 presents the forecast for SAF production out to 2050. We projected that SAF replaces about 0.5% and 47% of the conventional jet fuel production by 2035 under the most pessimistic and optimistic scenarios, respectively. By 2050, these values could rise to about 7% and 87%, respectively.

Table 3. Codes and maturity level definitions given to the announcements in the short-term database.

Parameter	Criterion
Code	
1	SAF production/facility planned.
2	SAF targeted/mentioned. The company has no specific plans regarding SAF production but mentions something like "we will make green diesel and jet fuel."
3	Process relevant to SAF. The company does not indicate their willingness to produce jet fuel, but the process could theoretically do so.
Maturity level	
A (Very high)	The company is already producing and selling renewable fuel produced using an ASTM qualified pathway.
B (High)	1. The company has one or more of the following: • A plant under construction • A demo or pilot plant built by the company or a partner. These plants depend on their technology maturity (e.g., for HEFA, a newcomer can build a plant) • Credibility of the partnership (e.g., financial backing) 2. Fuel is already certified for use by aviation
C (Moderate)	1. The company has not yet started to produce but has financial partners, off-take agreement, and/or some government support for technology scale-up to commercial demo. 2. The fuel readiness level is greater than or equal to 6 (equivalent to being under evaluation for approval). 3. The company has made some kind communication and/or public information regarding on-going activities over the last 12–18 months.

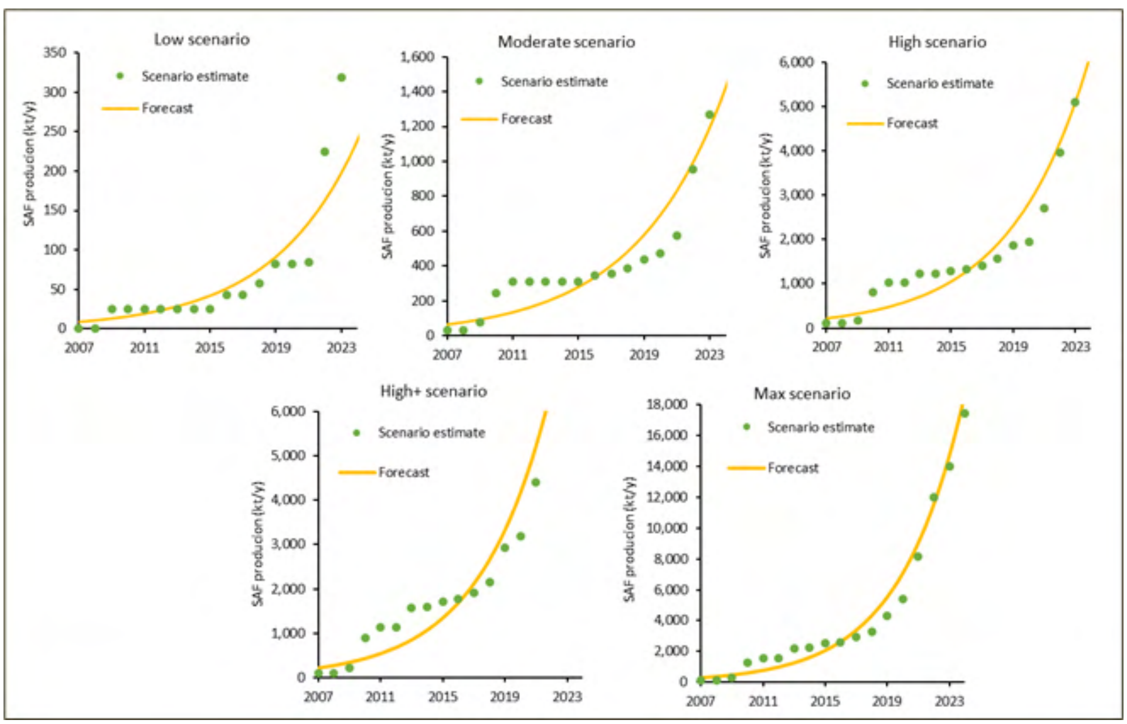


Figure 5. Ramp-up and curve fitting of the SAF production scenario results out to 2025.

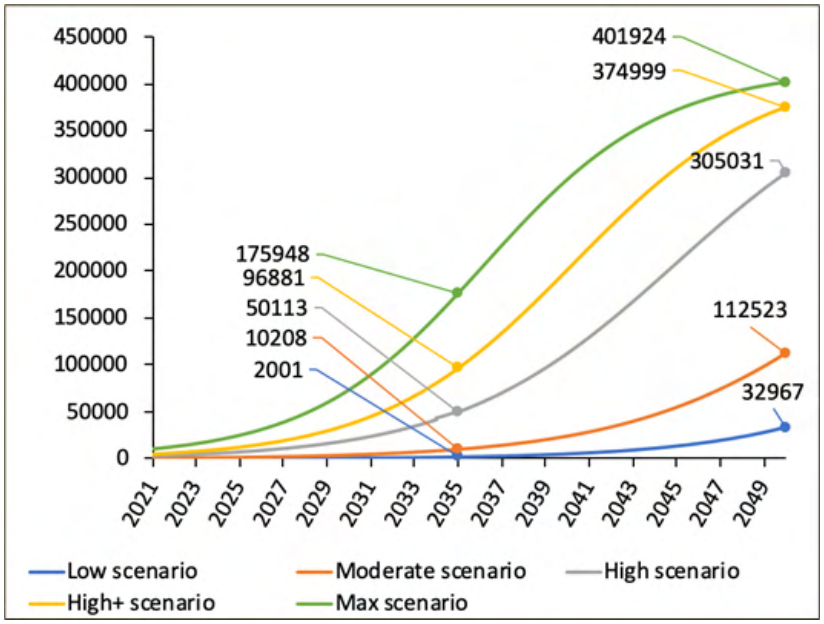


Figure 6. Forecasted SAF production out to 2050 under the analyzed scenarios. Data in kt.

Feedstock portfolios for short-term SAF production were estimated for 2021 considering the information included in the short-term projection database. The feedstock portfolio to 2035 was inferred considering the set of feedstock group-specific SAF production for the year 2050, which was developed during CAEP/10 (see CAEP/10-IP13) assuming a linear evolution of the feedstock breakdown (from 2021 to 2050). These feedstock groups differ in their sustainability assumptions (the "S"-dimension of the analysis with five scenarios), their price and policy emphasis on bioenergy in general (the "A" dimension with 3 scenarios), and their emphasis on SAF production (the "F" dimension with 5 scenarios). Lower A and F values indicate a higher emphasis on bioenergy and SAF, respectively. Thus, the max, high+, high, moderate, and low SAF production scenarios considered a high (A1 and F1 dimensions), moderate (average A1/A2 and F2 dimensions), middle (A2 and F2 dimensions), low (average A2/A3 and F3 dimensions), and very low (A3 and F3 dimensions) emphasis on bioenergy and SAF production, respectively. All SAF production scenarios considered a middle availability of primary sustainable feedstocks (average S2/S3 dimension). Figure 7 shows the evolution of the feedstock portfolio to produce SAF under the analyzed scenarios.

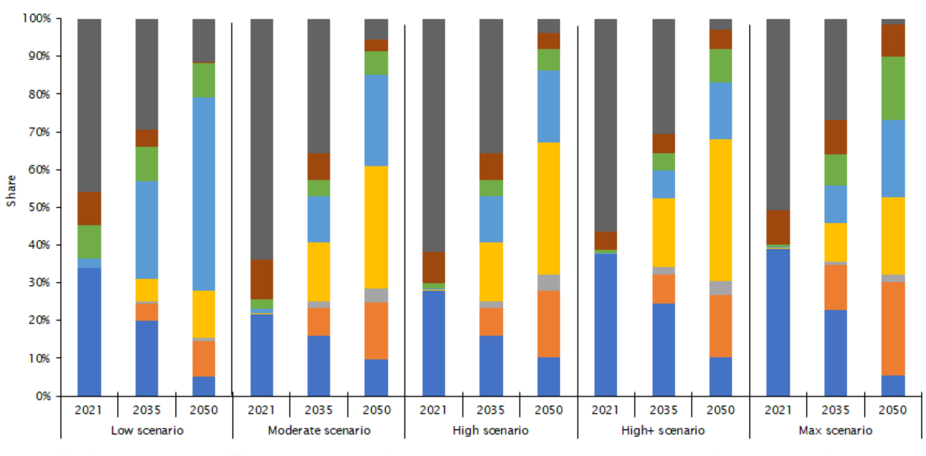


Figure 7. Feedstock portfolio for SAF production in 2021, 2035, and 2050.

Availability scenarios for fuels using waste CO_2 and atmospheric CO_2

We considered three scenarios for fuel availability, defined based on the attainability and readiness of advanced fuel production technologies and certification processes:

- IS1 (low end of the range of potential GHG reductions): high attainability and readiness of fuel production technologies and certification processes. However, waste CO_2 volumes are limited to the most economic sources. Few incentives exist for SAF production.
- IS2 (the middle-of-the-range of potential GHG reductions): medium attainability and readiness for fuel production technologies and certification processes. Use of waste gases for SAF production with expanded waste resource volumes is acknowledged. Increased incentives exist for SAF and LCAF production.
- IS3 (high end of the range of potential GHG reductions): Low attainability and readiness of advanced fuel production technologies and certification processes. Use of both waste and atmospheric gases is assumed. High incentives for GHG emissions reduction.

In each of the integrated scenarios, we assumed that CO_2 came from different subsets of waste CO_2 streams:

- IS1 considers only CO_2 capture from ethanol and ammonia sources with relatively low cost ($20-30 USD per tonne CO_2 for ammonia and ethanol vs. ~$110 USD per tonne CO_2 for iron, steel and cement sources). Fuel conversion is modeled based on the alcohol-to-jet process, with a fuel yield of 0.204 t fuel/t CO_2 at a fraction of jet fuel in the output slate of 70%. In addition, the availability of renewable electricity is considered a potentially limiting factor for producing waste CO_2-based fuels, with power generation limits derived from the International Energy Agency's Stated Policy Scenario.
- IS2 considers CO_2 capture from ethanol and ammonia sources, as well as from the production of iron, steel and cement, given the wide availability of waste CO_2 capture technologies. Fuel conversion is modeled based on the Fischer-Tropsch process, with a fuel yield of 0.272 t fuel/t CO_2 at a fraction of jet fuel in the output slate of 41%. In addition, the availability of renewable electricity is considered a potentially limiting factor for producing waste-CO_2-based fuels, with power generation limits derived from the International Energy Agency's Sustainable Development Scenario.
- IS3 considers the same waste CO_2 sources as IS2, but we model reduced CO_2 availability due to the use of carbon capture and storage following Paltsev et al., 2021. Fuel conversion is assumed based on the Fischer-Tropsch process with a fuel yield of 0.272 t fuel/t CO_2 at a fraction of jet fuel in the output slate of 41%in the same way as IS2. Direct air capture is considered as another source of CO_2 under IS3, with its scale-up being limited according to additional capacity build-up beyond the International Energy Agency's Net Zero Emissions Scenario 2050. In addition, the availability of renewable electricity is considered a potentially limiting factor for production of waste- and atmospheric-CO_2-based fuels, with power generation limits derived from the International Energy Agency's Net-Zero 2050 Scenario.

The potential volumes of fuel from waste gases and atmospheric CO_2 are shown in Figure 8. The integrated scenarios allow the use of different sources of CO_2 and therefore produce different volumes of fuel over time. In IS1 (considering waste CO_2 from ethanol and ammonia only), up to 0.05 Gt/y of jet fuel can be produced from 2040 on. In IS2, the additional use of CO_2 from iron, steel, and cement plants allows a scale-up to 0.3-0.35 Gt/y in the year 2070. In IS3, a mix of fuel production leveraging waste and atmospheric CO_2 reaches 0.35 Gt/y, with an increasing share of direct air capture-based fuels over time as the availability of direct air capture scales up and waste CO_2 streams decrease due to the increased use of carbon capture and storage technologies.

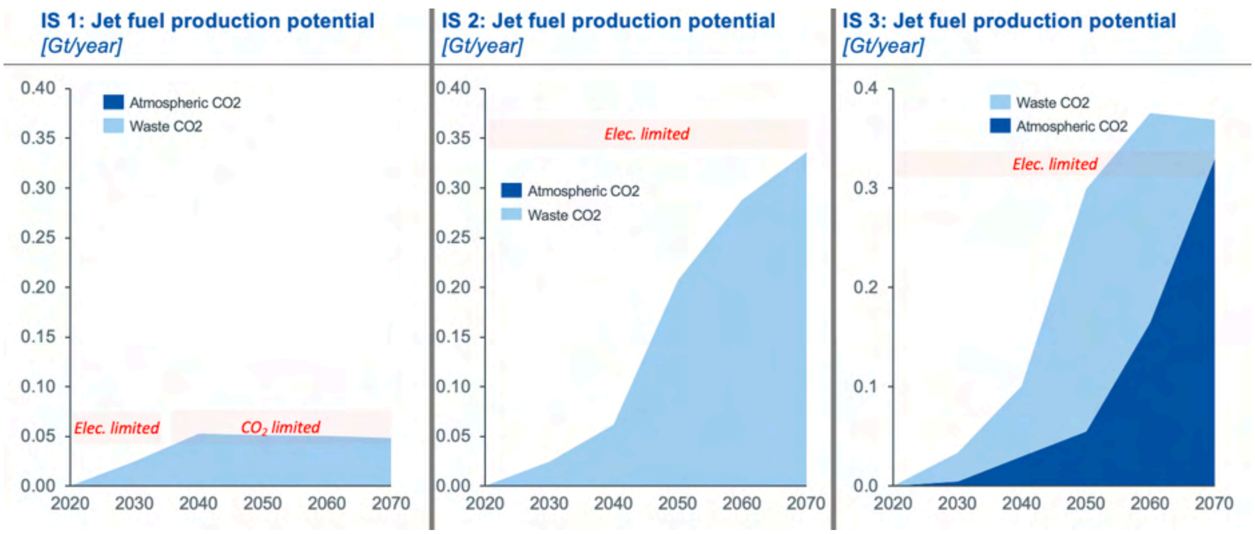


Figure 8. Production potential of PtL fuels in three integrated scenarios using either waste CO_2 (IS1, IS2) or both waste and atmospheric CO_2 (IS3).

Milestone

The work described above has been documented in several Working Papers submitted to the FTG. In addition, both the SAF production scenarios and the fuel production scenarios for fuels produced from waste CO_2 and atmospheric CO_2 provide the scientific basis for the fuel availability assessments under LTAG.

Major Accomplishments

- The team developed comprehensive scenarios of future availability of SAF, presented them to FTG, and provided the data as input to LTAG.
- The team developed comprehensive scenarios of future availability of drop-in fuels produced using Waste CO_2 or Atmospheric CO_2 sources. The data is an input to the LTAG analyses.

Publications

CAEP/12-FTG/06-WP/07: Summary of progress of the Technology Production Policy Task Group. November 2020.
CAEP/12-FTG/07-WP/04: Method for SAF production projections out to 2035. February 2020.
CAEP/12-FTG/07-FL/06: Proposal for the addition of a "SAF-emphasis scenario". February 2021.
CAEP/12-FTG/08-WP/02: Summary of SAF production scenarios and associated GHG emissions reductions. March 2021.
CAEP/12-FTG/08-IP/02: SAF production scenarios and associated GHG emissions reductions. March 2021.
CAEP/12-FTG/08-FL/04: Additional caveats for the reporting of the SAF production scenarios and associated GHG emissions reductions as presented in CAEP/12-FTG/08-WP/02 and IP/02. March 2021.

Outreach Efforts

Progress on these tasks was communicated during weekly briefing calls with the FAA and other U.S. delegation members to FTG, as well as during numerous FTG teleconferences between meetings. In addition, UHasselt and MIT experts participated in and contributed to numerous FTG meetings, including FTG/06 (November 2020), FTG/07 (February 2021), FTG/08 (March 2021), FTG/09 (May 2021), and FTG/10 (July 2021).

Furthermore, results on fuels from waste CO_2 and atmosphericCO_2 were briefed to the LTAG Fuels subgroup in a detailed presentation on May 12, 2021. The team also engaged in detailed discussions with LTAG experts and participated in bi-weekly meetings of the LTAG Fuels subgroup.

The results from the fuel production assessment for CORSIA-eligible fuels were also presented during the ASCENT meeting in Spring 2021.

Awards
None

Student Involvement
None

Plans for Next Period
The team will continue to update scenarios and projections as needed.

Task 4 – Develop Methods for Probabilistic Life-cycle Analyses and Probabilistic Techno-economic Analyses of SAF
Massachusetts Institute of Technology

Objective
Previous studies have shown significant variability and uncertainty in the life cycle emissions of renewable drop-in fuels (e.g., Sills et al., 2012, Fortier 2014). This variability has been addressed by calculating local sensitivities and generating a deterministic range of estimates including maximum, minimum, and most likely values (e.g., Staples et al. 2014, Stratton et al., 2011, Seber et al. 2014, Galligan 2018, Rosen 2017). Uncertainty has been quantified for selected pathways (Suresh et al., 2018); however, a probabilistic quantification of uncertainty across SAF pathways has not yet been performed.

Similarly, MIT previously conducted stochastic techno-economic analysis (TEA) studies for a wide set of feedstock-to-fuel pathways to convert biomass or industrial and household wastes into alternative aviation fuel in the U.S. The resulting literature (e.g., Bann et al., 2017; Yao et al., 2017; Suresh et al., 2018; Pearlson et al., 2013, Seber et al., 2014; Bond et al., 2014; Staples et al., 2014) shows that alternative aviation fuels will remain more expensive to produce than conventional jet fuel in the short- to medium-term, but also highlights the range of potential cost outcomes.

Previous TEA and LCA studies have evaluated nationwide uncertainty but did not intend to capture or disentangle nationwide uncertainty from regional variability in key inputs. Regional variability manifests itself in factors such as yield, utility prices, emissions factors, and capital area cost factors. Under this task, we aim to develop a high-resolution stochastic TEA and LCA model to disentangle the impacts of regional variability and nationwide uncertainty in key input parameters on costs and lifecycle impacts. The results of a combined probabilistic LCA would help researchers, policymakers, technology developers, and investors systematically evaluate the risks and likely emissions outcomes of SAF production and use. In addition, disentangling variability from uncertainty would guide decisionmakers in choosing the most efficient implementation strategies.

These analyses are presented in the context of a fuel production assessment for the U.S. by the year 2035 and provide further insights into the potential for the U.S. to meet certain SAF production goals through domestic SAF production, while accounting for the uncertainties and variabilities associated with future production.

Research Approach
The analysis followed a three-step approach as shown in Figure 9.

First, we calculated feedstock availability in 2035 (for the 15 feedstocks considered) at the county level. Mass and energy balances, for the six feedstock-to-fuel pathways we considered, were modeled based on existing literature. The costs and lifecycle emissions associated with feedstock production, transportation, fuel production, and fuel transportation were quantified using regional data and while accounting for uncertainty. Airport jet fuel demand was calculated at the county level from flight schedule data. For any uncertain inputs or assumptions, Monte Carlo analysis was performed.

Second, based on the costs and emissions model for each feedstock and pathway at each viable location, we ran a supply chain optimization model to determine the minimal-cost SAF supply chain for each run case, subject to the airport jet fuel demand requirements. The model was run across four different land use scenarios for 2035, which make different assumptions about the amount of land that will become available for energy crop cultivation. Additionally, the optimization model was run for two different carbon emissions costs (\$0/tonne CO_2e and \$100/tonne CO_2e), to evaluate the impact of carbon pricing on supply chain costs and emissions.

Third, we calculated key outputs, including cost-minimal SAF availability, costs, and GHG emission savings. These metrics allow us to compare the proposed SAF system and traditional petroleum-derived jet fuel.

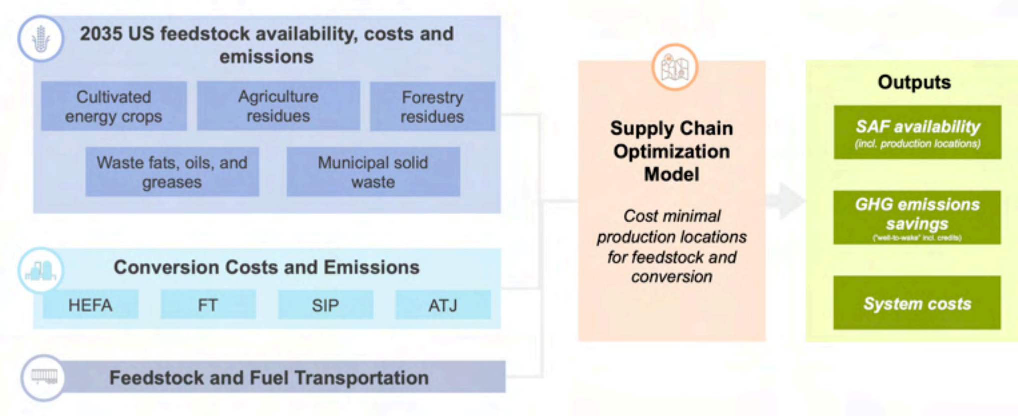
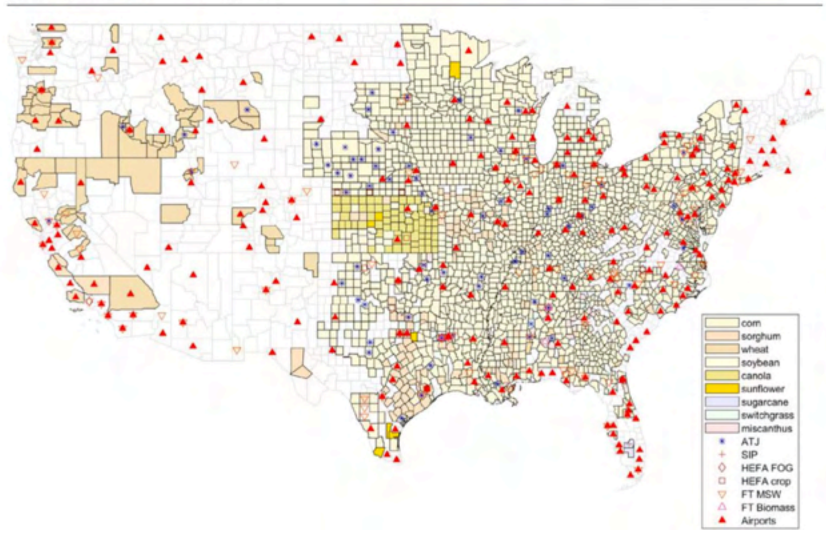


Figure 9. Method of the year-2035 fuel production assessment with stochastic LCA and TEA.

Across all land use scenarios considered, the maximum fraction of jet fuel demand that can be reached is 77.6%. Figure 10 shows the cost-optimal locations for feedstock farms and biorefineries to meet 50% of jet fuel demand in 2035.

Introducing a carbon price had significant impacts on the supply-chain layout. Specifically, a carbon price increased the share of feedstock and conversion pathways with slightly higher costs but lowered lifecycle GHG emissions. In fact, the average per-unit SAF emissions across the supply chain was calculated at 54.1 gCO_2e/MJ without a carbon price. this value declined to 36.6 gCO_2e/MJ with the introduction of a US\$100/tCO_2e carbon price. The average per-unit SAF costs were \$0.75/L and \$0.78/L without and with a carbon cost, respectively. Detailed insights into the supply-chain changes are shown in Figure 11.

Supply chain map of a cost-optimized supply chain meeting 50% jet fuel demand



	SAF cost ($/L)	GHG emissions (gCO_2e/MJ)	SAF produced [bn gal]	# plants
AtJ	0.71 [0.63-0.81]	64 [56.5-74.4]	7.33 [4.3-9.9]	72 [44-93]
HEFA crop	0.68 [0.59-0.79]	71.7 [60.9-83.5]	0.60 [0-1.6]	7 [0-22]
HEFA FOG	0.60 [0.49-0.75]	22.7 [21.0-25.0]	0.40 [0.3-0.4]	6 [4-6]
SIP	0.84 [0.52-1.14]	49.5 [34.7-67.9]	0.4 [0.3-0.4]	1 [0-19]
FT Biomass	0.88 [0.79-1.01]	7.6 [4.4-10.3]	2.44 [0.2-5.1]	72 [4-144]
FT MSW	0.36 [0.29-0.46]	25.6 [19.5-31.6]	1.95 [1.8-2.0]	106 [100-111]

Figure 10. Results from the supply chain optimization under a 50% mandate and optimistic yield.

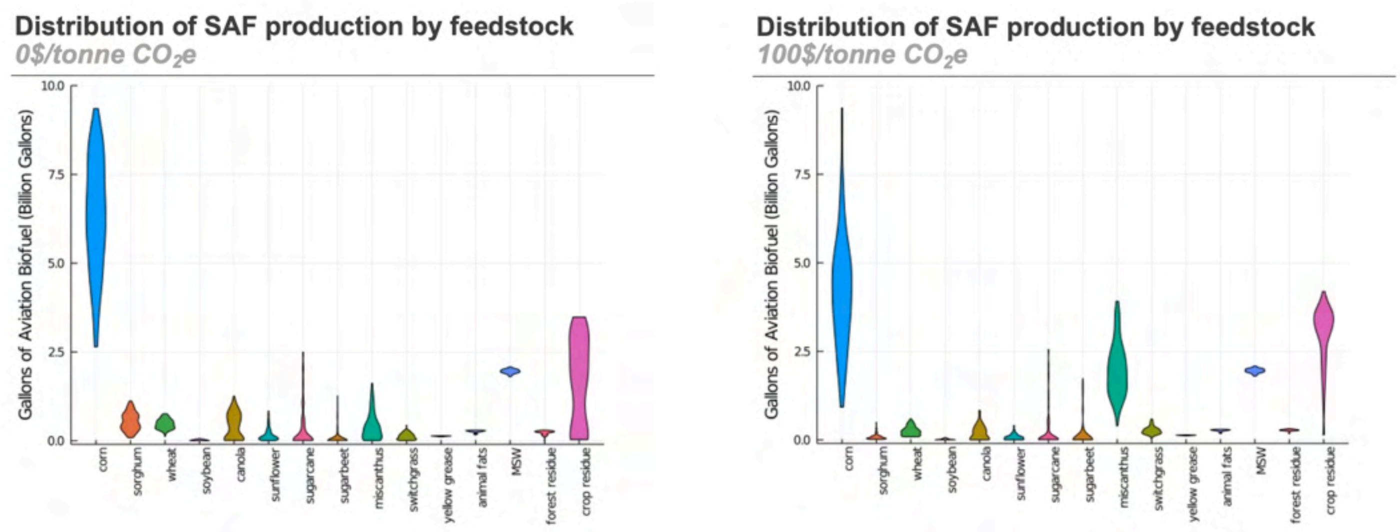


Figure 11. Carbon price sensitivity of the year-2035 feedstock mix under a 50% mandate and optimistic yield.

Milestone
A baseline analysis has been completed and is being prepared for publication in the scientific literature.

Major Accomplishments
A baseline analysis has been completed and is being prepared for publication in the scientific literature.

Publications
Kelso, W. (2021). Cost optimization of U.S. sustainable aviation fuel supply chain under different policy constraints [S.M. Thesis, Massachusetts Institute of Technology]. *To be released soon via MIT DSpace*: https://dspace.mit.edu/

Wang, Z., Staples, M. D., Tyner, W., Zhao, X., Malina, R., Olcay, H., Allroggen, F., & Barrett, S. R. H. (2021). Quantitative policy analysis for sustainable aviation fuel production technologies. Frontiers in Energy Research, *9*. https://doi.org/10.3389/fenrg.2021.751722

Outreach Efforts
MIT presented the work under this task to the ASCENT 1 Team meeting in August 2021.

Awards
None

Student Involvement
The MIT graduate student involved in this task was Walter Kelso, who graduated in the Summer of 2021.

Plans for Next Period
MIT will continue to apply and refine the model. Specifically, the team will add Power-to-Liquid and Power-and-Biomass-to-Liquid pathways and will add assessments of water use. With these additions, the team will conduct further policy analyses.

References
Bann, S. J., Malina, R., Staples, M. D., Suresh, P., Pearlson, M., Tyner, W. E., Hileman, J. I., & Barrett, S. (2017). The costs of production of alternative jet fuel: A harmonized stochastic assessment. Bioresource Technology, *227*, 179-187. https://doi.org/10.1016/j.biortech.2016.12.032

Bond, J. Q., Upadhye, A. A., Olcay, H., Tompsett, G. A., Jae, J., Xing, R., Alonso, D. M., Wang, D., Zhang, T., Kumar, R., Foster, A., Sen, S. M., Maravelias, C. T., Malina, R., Barrett, S. R. H., Lobo, R., Wyman, C. E., Dumesic, J. A., & Huber, G. W. (2014). Production of renewable jet fuel range alkanes and commodity chemicals from integrated catalytic processing of biomass. Energy & Environmental Science, *7*(4), 1500-1523. https://doi.org/10.1039/c3ee43846e

Fortier, M. P., Roberts, G. W., Stagg-Williams, S. M., & Sturm, B. S. (2014). Life cycle assessment of bio-jet fuel from hydrothermal liquefaction of microalgae. Applied Energy, *122*, 73-82. https://doi.org/10.1016/j.apenergy.2014.01.077

Galligan, T. (2018). *Carbon dioxide emissions reduction potential of aviation biofuels in the US* [Master's thesis, Massachusetts Institute of Technology]. Unpublished.

Pearlson, M., Wollersheim, C., & Hileman, J. (2013). A techno-economic review of hydroprocessed renewable esters and fatty acids for jet fuel production. Biofuels, Bioproducts and Biorefining, *7*(1), 89-96. https://doil.org/10.1002/bbb.1378

Rosen, C. (2017). Scenario based lifecycle analysis of greenhouse gas emissions from petroleum-derived transportation fuels in 2050 [Master's thesis, Massachusetts Institute of Technology].

Seber, G., Malina, R., Pearlson, M. N., Olcay, H., Hileman, J. I., & Barrett, S. R. (2014). Environmental and economic assessment of producing hydroprocessed jet and diesel fuel from waste oils and tallow. Biomass and Bioenergy, *67*, 108-118. https://doi.org/10.1016/j.biombioe.2014.04.024

Sills, D. L., Paramita, V., Franke, M. J., Johnson, M. C., Akabas, T. M., Greene, C. H., & Tester, J. W. (2012). Quantitative uncertainty analysis of life cycle assessment for algal biofuel production. Environmental Science & Technology, *47*(2), 687-694. https://doi.org/10.1021/es3029236

Staples, M. D., Malina, R., Olcay, H., Pearlson, M. N., Hileman, J. I., Boies, A., & Barrett, S. R. (2014). Lifecycle greenhouse gas footprint and minimum selling price of renewable diesel and jet fuel from fermentation and advanced fermentation production technologies. Energy & Environmental Science, *7*(5), 1545-1554. https://doi.org/10.1039/c3ee43655a

Stratton, R. W., Wong, H. M., & Hileman, J. I. (2011). Quantifying variability in life cycle greenhouse gas inventories of alternative middle distillate transportation fuels. Environmental Science & Technology, *45*(10), 4637-4644. https://doi.org/10.1021/es102597f

Suresh, P., Malina, R., Staples, M. D., Lizin, S., Olcay, H., Blazy, D., Pearlson, M. N., & Barrett, S. R. H. (2018). Life cycle greenhouse gas emissions and costs of production of diesel and jet fuel from municipal solid waste. Environmental Science & Technology, *52*(21), 12055-12065. https://doi.org/10.1021/acs.est.7b04277

Yao, G., Staples, M. D., Malina, R., & Tyner, W. E. (2017). Stochastic techno-economic analysis of alcohol-to-jet fuel production. Biotechnology for Biofuels, *10*(1). h10.1186/s13068-017-0702-7

Task 5 – Support Coordination of All A01 Universities' Work on SAF Supply-chain Analyses

Massachusetts Institute of Technology

Objective

The objective of this task is to provide support for coordination of all ASCENT Project 1 (A01) Universities' work on SAF supply-chain analysis. The sharing of methods and results decreases the replication of A01 Universities' work on similar topics.

Research Approach

The MIT A01 team performed several functions to accomplish this task. Specifically, the team:

- Participated in the bi-weekly A01 coordination teleconferences, which were used as a venue to discuss progress on various grant tasks and learn about the activities of other ASCENT universities. The team also presented current research on co-processing to the A01 universities.
- Contributed to efforts for developing a special journal issue on SAF based on the research conducted under A01.

Milestone

The MIT ASCENT A01 team presented current research to other ASCENT universities.

Major Accomplishments
The major accomplishments associated with this task include participation in bi-weekly A01 coordination teleconferences; presentation of current research to other ASCENT universities; and contribution to the development of a journal special issue.

Publications
N/A

Outreach Efforts
See above.

Awards
None

Student Involvement
N/A

Plans for Next Period
Continued engagement in bi-weekly teleconferences and other events to disseminate MIT's A01 work.