



Project 052 Comparative Assessment of Electrification Strategies for Aviation

Massachusetts Institute of Technology

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- P.I.: Dr. Florian Allroggen
- FAA Award Number: 13-C-AJFE-MIT, Amendment Nos. 062, 072, 080, 093, 098, 115, 121, 128, 133, 138, and 143
- Period of Performance: February 5, 2020, to August 31, 2027
- Tasks (reported for the period October 1, 2024, to September 30, 2025):
 1. Develop a suite of roadmaps for aircraft electrification (covered in previous reporting periods; not reported for this period)
 2. Develop a system-level engineering model of power conversion processes and aircraft energy requirements
 3. Develop a model for analyzing the economics and emissions of electrification strategies (improved modeling capabilities for liquid methane (LCH₄) covered under Task 2 for more coherent presentation).
 4. Analyze the system-level costs and benefits of the electrification strategies
 5. Analyze the benefits of energy storage for power-to-liquid (PtL) fuel production (covered in previous periods; not reported during the current reporting period)

Project Funding Level

\$2,185,000 Federal Aviation Administration (FAA) funding and \$2,185,000 matching funds. Sources of match are approximately \$404,100 from MIT, plus 3rd party in-kind contributions of \$460,000 from NuFuels, LLC, and \$110,000 from Savion Aerospace Corporation, and \$214,000 from Google, LLC, and \$996,900 from Earth Force Technologies.

Investigation Team

Dr. Florian Allroggen, (P.I.), All tasks
Dr. Raymond Speth, (co-P.I.), Tasks 1, 2, and 4
Dr. Niamh Keogh, Tasks 2 and 4





Dr. Prashanth Prakash, Task 1, 2, and 4
Dr. Nicolas Gomez-Vega, (postdoctoral associate), Task 2
Dr. Arthur Brown, (postdoctoral associate), Task 4
Bjarni Kristinsson, (graduate researcher), Task 2

Project Overview

The long-term goal of this project is to quantify the costs and impacts of various electrification approaches for commercial aviation. The electrification pathways include battery-electric (“all-electric”) aircraft, as well as aircraft using drop-in sustainable aviation fuels (SAF) made with substantial electricity input (PtL) and electricity-intensive non-drop-in fuels, such as liquid hydrogen and methane. The project helps identify the best approach for using one unit of electric energy to power aviation. For this purpose, we develop both system-level engineering and system-level economic models, to assess electricity generation, fuel production, fuel transportation and storage, aircraft energy requirements, and aircraft operations. The models analyze different electrification pathways by using what can be described as a “power station to wake” approach. They quantify differences in costs and impacts associated with each electrification approach and compare them to a set of baseline aircraft powered by petroleum-derived fuels or drop-in SAFs made from biomass or waste streams. The outputs are used in a cost-benefit analysis, which provides insights into the net benefits associated with each technology.

Task 2 – Develop a System-level Engineering Model of Power Conversion Processes and Aircraft Energy Requirements

Massachusetts Institute of Technology

Objective

The goal of this task is to develop and apply system-level models of the value-chain power conversion processes, including energy generation, conversion into an energy carrier, transportation, and use onboard the aircraft. The goal of this effort is to understand which fuel most efficiently uses energy to power aviation. In the reporting period, we have made progress on two research streams within Tasks 2 and 3 (both are discussed here for cohesive presentation):

1. *Evaluation of supply chains for non-drop-in energy carriers for aviation:* Activities during this reporting period cover a detailed study of LCH₄ as an energy carrier for aviation, including challenges and opportunities. Key questions include:
 - a. How much methane can be produced annually via biogenic material, including consideration of methanation from waste gas streams?
 - b. What is the feasibility of supply chains, including placement of liquefaction facilities, associated utilities and fuel tanks, and costs across different airports?
 - c. How much CH₄ will leak from the supply chain, including assessing the first-order impacts of such leakage?
2. *Detailed modeling and sizing of aircraft and their subsystems:* Activities during the reporting period include improving our understanding of the aircraft performance implications of different non-drop-in carriers. Areas of focus include:
 - a. Modeling of hydrogen-fueled aircraft including their off-design performance
 - b. Design and analysis of methane-fueled aircraft
 - c. Advances for modeling fuel-cell powered aircraft design
 - d. Development of a modular engine simulation model that could work with alternative propulsion architectures and new fuels

This work builds on accomplishments in previous periods on (1) how the design of the fuel tank affects hydrogen aircraft energy demand and (2) how heat exchangers can be integrated into the jet engine to reduce energy demand. Higher fidelity models were developed, including capabilities to assess off-design performance, detailed turbomachinery performance maps, and a model for how turbine cooling affects engine performance. Such capabilities extend to unconventional propulsion systems for which new models are needed. While there are existing engine models that could handle a broad set of propulsion architectures, these are slow and not well suited for optimization at the aircraft level.



Milestones

Evaluation of Alternative Non-drop-in Energy Carriers for Aviation

- Selected LCH₄ for detailed analysis. The preliminary results remain promising and the team continues to refine the system-level assessment.
- Completed a preliminary value chain model of producing LCH₄ via anaerobic digestion, considering waste and residue feedstocks.

Detailed Aircraft and Subsystem Modeling

- Completed the aircraft design models for cryogenic fuels with turbofan propulsion. Two conference papers have been prepared to disseminate the findings at American Institute of Aeronautics and Astronautics (AIAA) SciTech. A poster was prepared for the FAA ASCENT Fall meeting.
- Developed a preliminary version of a propulsion system model, named PowerCycles.jl, with much higher computational speed than existing open-source alternatives. This model is coupled to the MIT Transport Aircraft System OPTimization (TASOPT) tool to enable a broader set of propulsion architectures.
- Merged models for fuel-cell-powered aircraft using ducted fans and electric motors into TASOPT.jl. The models are ready to be used to design aircraft using fuel cells as an energy conversion system.

Major Accomplishments

Detailed Study of the LCH₄ Supply Chains for Aviation

During the current year, a detailed supply chain model for LCH₄ production was built under this project. It includes (but is not limited to) the following elements:

Methane Production Pathways

Multiple routes are available to produce methane as shown in Figure 1. Anaerobic digestion of biomass is the predominant pathway. It produces, on average, a 1:1 molar ratio of methane and carbon dioxide (CO₂). For the biomethane to be viable for commercial use, the biogenic CO₂ must be removed. The stream of biogenic carbon dioxide can be mixed with hydrogen to produce methane via three routes (see Figure 1). The methanation (Sabatier reaction) is the preferred pathway as the preferred nickel catalyst is low cost for a chemical catalyst, and the reaction has on the order of 95% methane selectivity at approximately 650 K and 5 bar.

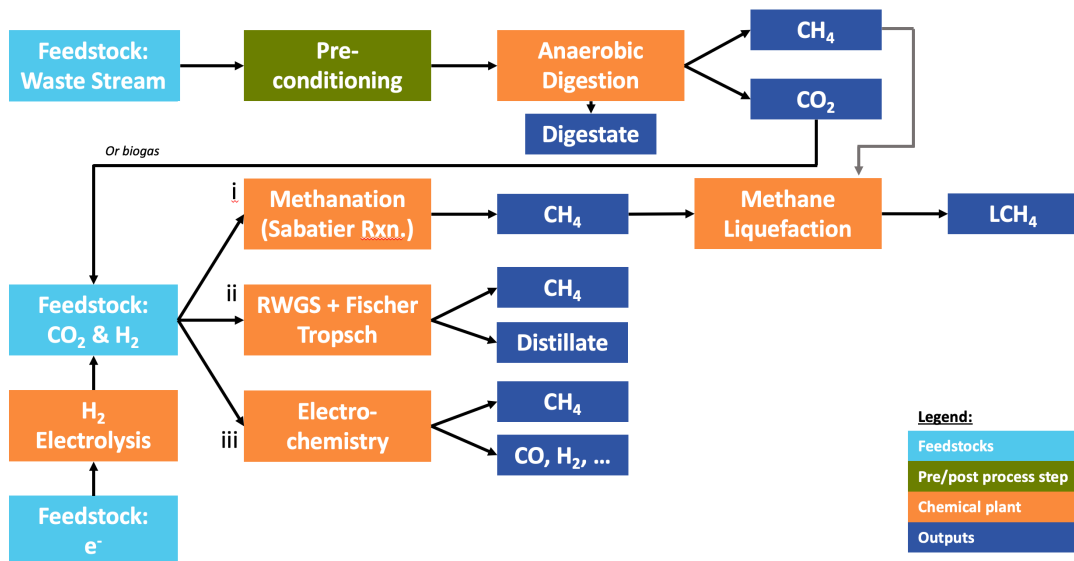


Figure 1. Overview of potential methane synthesis pathways.



Methane Production Potential

In 2019, the aviation industry consumed roughly 12 EJ of primary energy from jet fuel. In the first pass, we assess how 12 EJ of methane could be produced from biomass sources via anaerobic digestion. Sixteen waste and residue feedstocks were identified as potential scalable sources of CH₄, based on the literature's availability of conversion yields via anaerobic digestion. The literature search was focused on significant sources of available waste, and residues found by ASCENT Project 093's work. Figure 2 summarizes the availability of these 16 feedstocks considered, and their methane yields. Anaerobic digestion with pretreatment of all available feedstocks (mean residue scenario) results in 12 EJ of methane (lower heating value) on an annual basis. Note that not all of this potential CH₄ can be economically produced due to local availability and macro-economic factors (cost of debt, cost of equity).

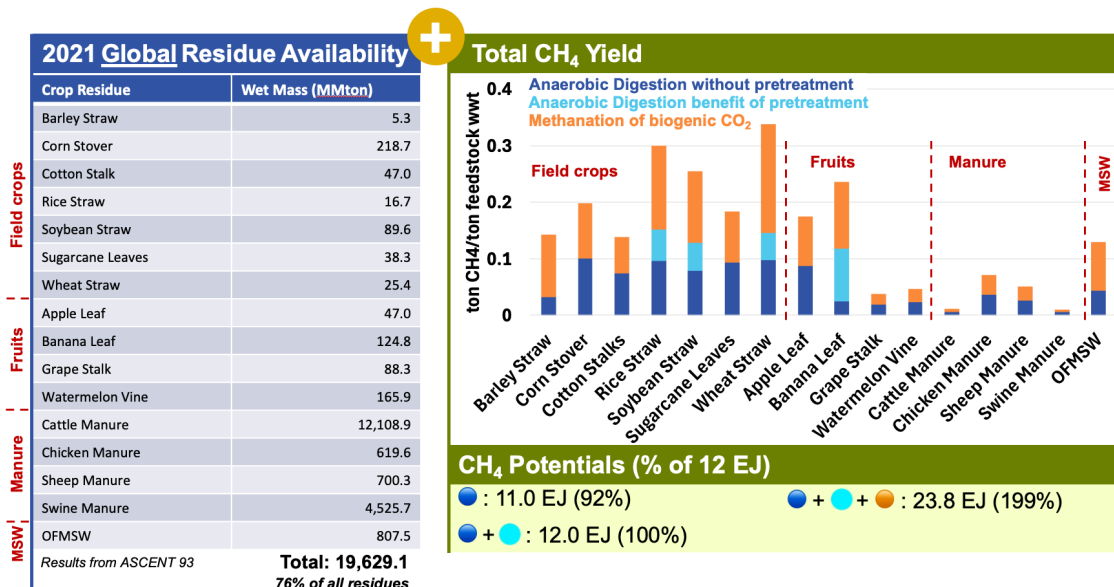


Figure 2. Residual biomass availability (mean residue scenario) and conversion yields to methane. Values are preliminary.

Technoeconomic Analysis of LCH₄ Production

Technoeconomic analysis can provide insight into the competitiveness of methane via anaerobic digestion from an economic angle. A discounted cash flow rate of return model was created to simulate the operational lifetime of an anaerobic digestion facility and determine the minimum selling price for methane in different locations.

An algorithm was then developed to allocate the limited supply of methane to airports globally. The goal was to have a fast algorithm that represents how a global supply chain of methane may develop, without sizing and modeling the whole supply chain network in detail. Figure 3 shows the model results for at-pump LCH₄ mean minimum selling price (MSP) at United States (U.S.) airports. A mean residue scenario is utilized, and the fuel demand from narrowbody aircraft is considered only (40-45% of global aviation fuel demand). The liquefaction premium of methane in the U.S. is modelled to be \$0.43/gal Jet-A on an equivalent energy basis.

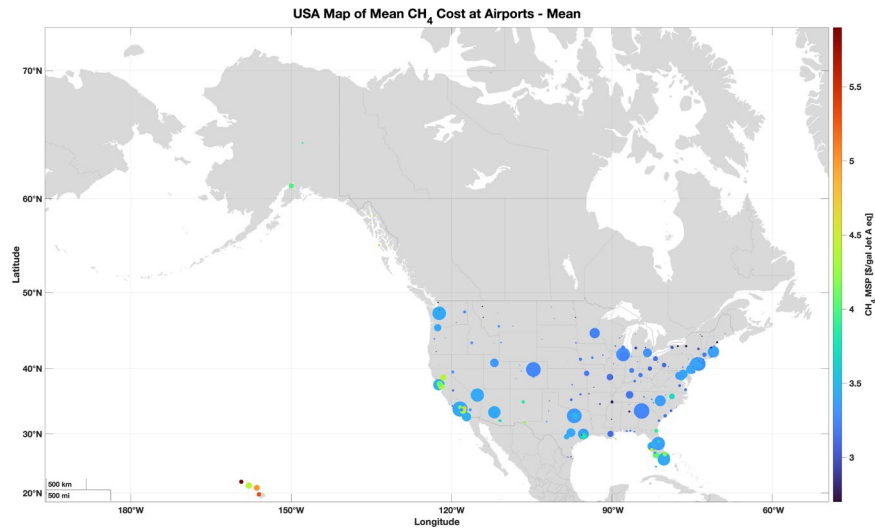


Figure 3. Preliminary liquid methane (LCH₄) pump price at United States airports, assuming only methane (CH₄) produced via anaerobic digestion and the mean residue-waste scenario.

Figure 4 displays the global at-pump price of LCH₄ at airports. The MSP is given in \$/L Jet A on an equivalent energy basis to allow for better comparison with jet fuel costs.

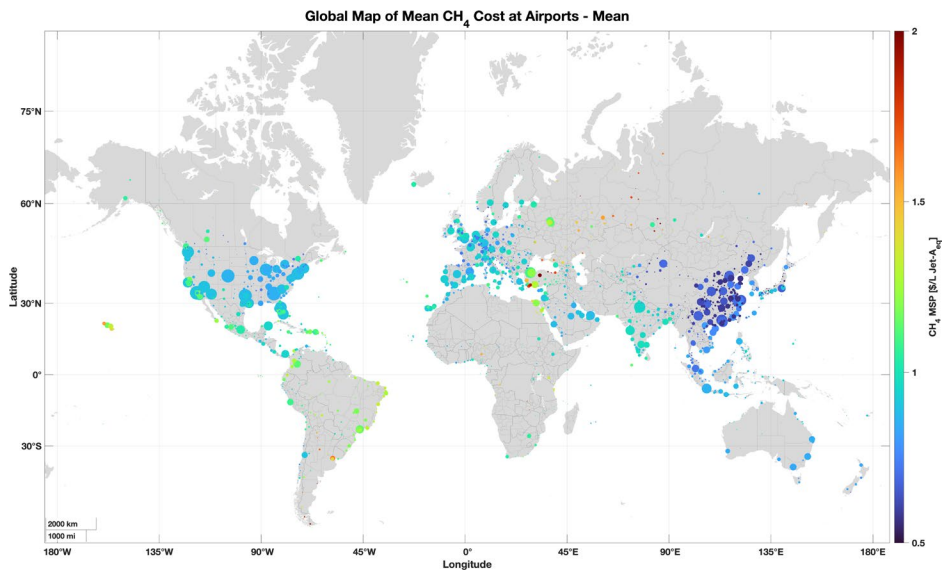


Figure 4. Preliminary liquid methane (LCH₄) pump price at airports globally, assuming only methane (CH₄) produced via anaerobic digestion and the mean residue-waste scenario.

Detailed Aircraft and Subsystem Modeling

Hydrogen-fueled Aircraft

In the studies conducted in the previous reporting period, hydrogen aircraft were optimized to complete one sizing mission. In the updated studies developed during this reporting period, the objective was to minimize the sum of the normalized energy demands across one sizing mission and four off-design missions with different ranges and ground temperatures (see Table 1). This is important as aircraft are regularly used on missions which do not match their design mission. The sensitivity parameters were chosen given their potential impacts on aircraft design, fuel tank, and engine



performance. The range in off-design missions 1 and 2 represents the 75% percentile by passenger-mile of missions flown by representative aircraft according to the 2019 OAG dataset; the range in off-design missions 3 and 4 represents the 50% percentile. The ground temperature in the sizing mission and off-design missions 1 and 3 is the standard sea-level temperature; the (higher) ground temperature in off-design missions 2 and 4 represent takeoff on a summer day.

Table 1. Payloads, ranges, and ground temperatures for the sizing and off-design missions.

	Short haul	Medium haul	Long haul
Payload in sizing mission (t)	11.50	17.55	38.59
Payload in off-design missions (t)	11.89	20.47	46.93
Range in sizing mission	4074 km (2200 nmi)	5556 km (3000 nmi)	14445 km (7800 nmi)
Range in off-design mission 1	1250 km (675 nmi)	2593 km (1400 nmi)	10556 km (5700 nmi)
Range in off-design mission 2	1250 km (675 nmi)	2593 km (1400 nmi)	10556 km (5700 nmi)
Range in off-design mission 3	833 km (450 nmi)	1759 km (950 nmi)	8334 km (4500 nmi)
Range in off-design mission 4	833 km (450 nmi)	1759 km (950 nmi)	8334 km (4500 nmi)
Ground temperature in sizing mission (K)	288.2	288.2	288.2
Ground temperature in off-design mission 1 (K)	288.2	288.2	288.2
Ground temperature in off-design mission 2 (K)	303.2	303.2	303.2
Ground temperature in off-design mission 3 (K)	288.2	288.2	288.2
Ground temperature in off-design mission 4 (K)	303.2	303.2	303.2

Figure 5 shows the payload-fuel energy intensity (PFEI; a non-dimensional measure of energy per passenger mile) for a jet fuel aircraft and hydrogen aircraft with two fuel tank options: a single-walled tank and a double-walled tank.

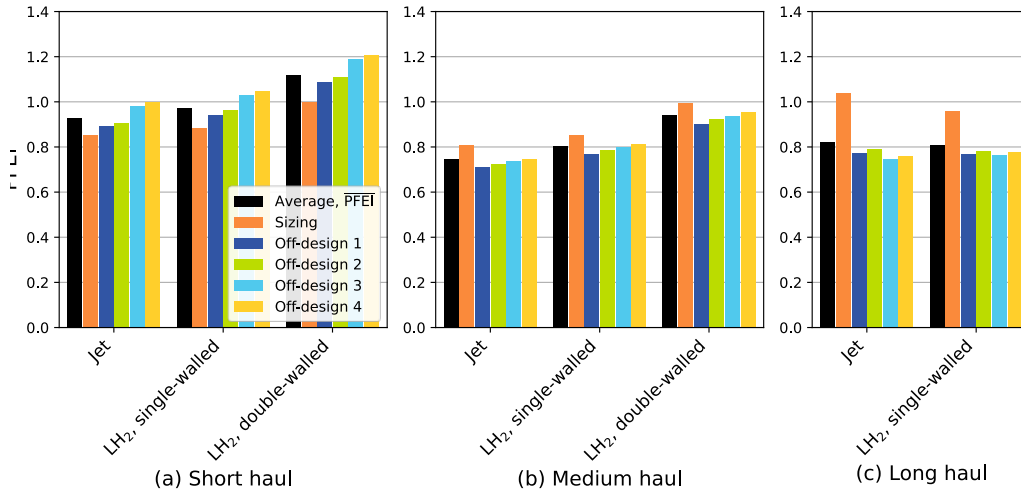


Figure 5. Normalized energy demand (payload-fuel energy intensity [PFEI]) for different aircraft fuels, fuel tank options, and missions.

Our previous study on heat exchangers integrated into the jet engine was revised with higher-fidelity models, including novel performance maps for the turbomachinery and a model for how cooling affects the efficiency of the engine’s turbine. The latter model had a significant effect on the results, making one of the heat exchanger placement options more attractive, namely the cooler of turbine cooling air. Figure 6 shows the relative change in aircraft parameters, including the thrust-specific fuel consumption (TSFC) and lift-to-drag ratio (L/D), averaged across the five design missions. The results show that improvements in normalized energy demand on the order of 10% are possible if multiple heat exchangers are used.

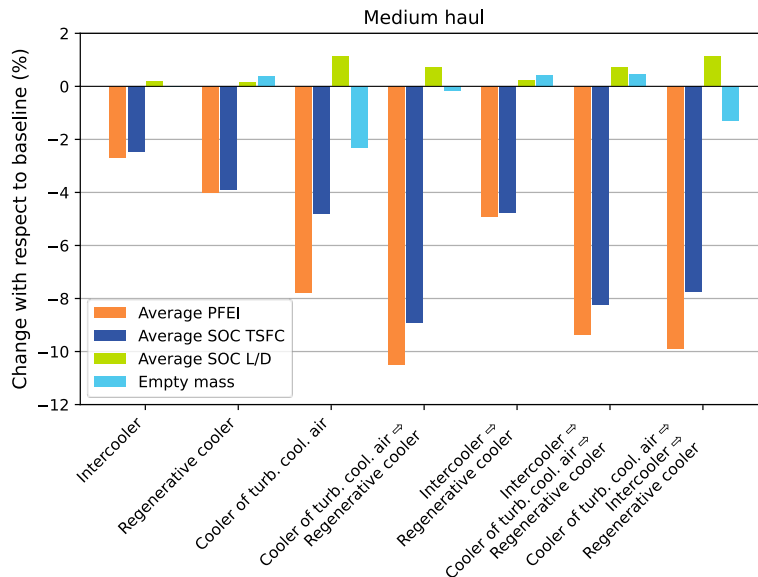


Figure 6. Relative change in hydrogen aircraft parameters with respect to a baseline with no heat exchangers. Thrust-specific fuel consumption (TSFC) and lift-to-drag ratio (L/D) values are at start of cruise (SOC).



Design and Analysis of Methane-fueled Aircraft

The aircraft design models for cryogenic fuels developed under ASCENT Project 052 were applied to design a liquid methane-fueled aircraft with a 250-passenger capacity and a range of 4,500 nautical miles; an equivalent jet-fuel aircraft was also designed for comparison. A preliminary mission-by-mission comparison of energy demand, as measured by a non-dimensional metric (the PFEI) is shown in Figure 7. Averaged across five missions (one sizing mission and four off-design missions), the methane aircraft has a 10.8% higher average PFEI than the jet-fuel analog, indicating a higher energy demand. We attribute this to the methane aircraft having a heavier fuselage as the fuel is carried in insulated fuel tanks in the fuselage, heavier wings due to the absence of bending moment relief from the fuel and increased drag due to the longer fuselage.

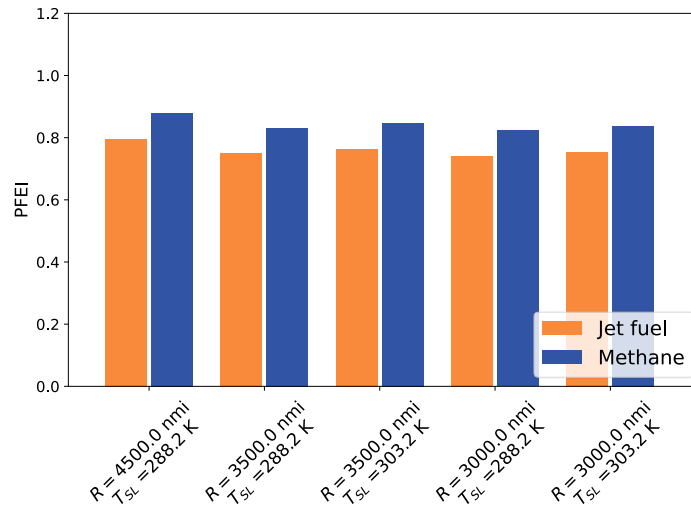


Figure 7. Energy demand (measured with payload-fuel energy intensity [PFEI]) of jet fuel and methane aircraft for one sizing and four off-design missions. Note that the mission ranges are not identical to those in Table 1.

Modular Engine Model

Our modular engine model can simulate the main components found in aircraft engines, such as compressors, turbines, burners or splitters, and combine them to form an independent engine. We have compared the performance of this engine model against the state-of-the-art open-source equivalent, pyCycle (Hendricks & Gray, 2019). In particular, we modeled the same high-bypass-ratio two-spool turbofan that is given as an example in the pyCycle source code. We find that our engine model produces results within 0.3% of the state at all stations in the engine. Comparing the runtimes, pyCycle with a tabular thermodynamic model takes 3.06 s to solve the design point of the turbofan engine and 7.85 s to solve both a design and off-design points; our engine model takes a median of 28.4 ms to solve the design problem and 37.7 ms to solve the off-design problem. This demonstrates that our model can already offer up to two orders of magnitude improvement in speed as compared to the best open-source alternative.

Publications

Presentations

- Gomez-Vega, N., Tan, D. Y., Prashanth, P., Barrett, S. R., Speth, R. L., & Allroggen, F. (2025, January). *Influence of Fuel Tank Design on the Energy Demand of Hydrogen Aircraft* [Conference presentation paper]. AIAA SCITECH 2025 Forum, Orlando, Florida, 1243. <https://doi.org/10.2514/6.2025-1243>
- Gomez-Vega, N., Prashanth, P., Speth, R. L., & Allroggen, F. (2025, January). *Hydrogen Aircraft Design With Heat-Exchanger-Enhanced Turbofan Engines* [Conference presentation paper]. AIAA SCITECH 2025 Forum, Orlando, Florida, 0089. <https://doi.org/10.2514/6.2025-0089>

During the reporting period, a journal paper expanding on these two conference papers was prepared and submitted for publication.



Outreach Efforts

Bjarni Örn Kristinsson shared the latest findings of the alternative non-drop-in energy carrier analysis at the 2025 ASCENT Spring meeting in Knoxville, Tennessee. A derivative of the 2025 ASCENT Spring presentation was given at the Zero Impact Aviation Alliance in May 2025, hosted at MIT. Dr. Gomez-Vega attended the AIAA SciTech 2025 conference in January 2025 in Orlando, Florida.

Student Involvement

During the reporting period, the MIT graduate student involved in this task was Bjarni Örn Kristinsson.

Plans for Next Period

Detailed Study of the LCH₄ Aviation System

- Complete the technoeconomic analysis of methanation via renewable energy sources.
- Develop an LCA model to estimate the gCO_{2eq}/MJ on a per-feedstock and country basis.
- Complete the LCH₄ analysis and submit a paper to a journal.

References

Hendricks, E. S., Gray, J. S. (2019). pyCycle: A tool for efficient optimization of gas turbine engine cycles. *Aerospace*, 6(8), 87. <https://doi.org/10.3390/aerospace6080087>

Task 4 – Analyze the System-level Costs and Benefits of the Electrification Strategies

Massachusetts Institute of Technology

Objectives

The objective of this task is to develop system-level analyses for comparing various electrification strategies while integrating the engineering and assessment models developed previously. During the current reporting period, the ASCENT Project 052 team focused on assessing the airport infrastructure required to replace current nine-passenger airliners (mostly regional air mobility [RAM]) with fully electric aircraft. Specifically, our team conducted a case study for Bethel Municipal Airport in Alaska. Estimates for number and type of chargers, airport power requirements for charging, and electric generation infrastructure (wind turbines, solar panels, and/or battery energy storage systems) were produced.

Research Approach

RAM is a category of airline service flying aircraft with few (≤ 9) seats to regional airports. About 550,000 such flights took place in the U.S. in 2019. RAM airliners are candidates for replacement with fully electric aircraft. This is because current batteries have low specific energy (energy per unit mass) relative to hydrocarbon fuels and are therefore too heavy to power single-aisle or long-haul airliners. By contrast, the small number of passengers and short ranges (typically ≤ 500 miles) of RAM flights means that battery-electric RAM airliners may be possible with current battery technology. Potential benefits of electric RAM include lower costs, particularly fuel and maintenance. In addition, tailpipe emissions from burning hydrocarbon fuels are eliminated.

The goal of this project is to assess the electrical infrastructure required to support battery-electric RAM operations. This is done in three steps. Firstly, a schedule of existing RAM flights is assembled from schedule data for the year 2019. Secondly, all flights are replaced with electric aircraft, and the electricity consumed during each flight is computed with a physics-based aircraft performance model. Finally, the electrical infrastructure required at each airport (i.e., chargers, electricity generation and transmission infrastructure, etc.) is assessed.

Milestones

- Selected Bethel, Alaska, for a case study. A dataset of RAM flights was assembled from OAG data using circular flights (flights that both departed from and arrived in Bethel, with one or more stops elsewhere).
- Estimated the number of chargers, power per charger, and airport electrical loads from charging based on a custom algorithm that used airline turnaround time requirements as an input.



- Sized electrical infrastructure (wind turbines, solar panels, and/or battery energy storage systems) to meet the charging loads using the National Laboratory of the Rockies' (NLR) Renewable Energy Optimization (REopt) tool. Power curtailment and cost estimates were obtained.

Major Accomplishments

Bethel, Alaska, was selected for a case study because it is the busiest airport in the U.S. by number of RAM arrivals, averaging about 65 per day in 2019. Bethel is not connected to the highway transport system, so the only way to reach Anchorage (the nearest large city) in a timely fashion is by air.¹ The RAM flights connect Bethel to dozens of outlying villages, each of which typically has a few hundred residents. Bethel is used as a hub for these flights because Bethel's airport (unlike those of the outlying villages) can handle single-aisle passenger airliners, which connect Bethel to Anchorage. Figure 8 shows a map of Alaska including Anchorage, Bethel, and the outlying connected villages. Figure 9 shows a map of the busiest RAM route in the area: the route from Bethel to the outlying villages of Kipnuk and Chefornak.



Figure 8. Map of Alaska showing Anchorage, Bethel (blue and black square), and the outlying villages connected to Bethel by RAM flights.

¹ 82% of communities in Alaska lack access to the road system and are similarly dependent on air travel.

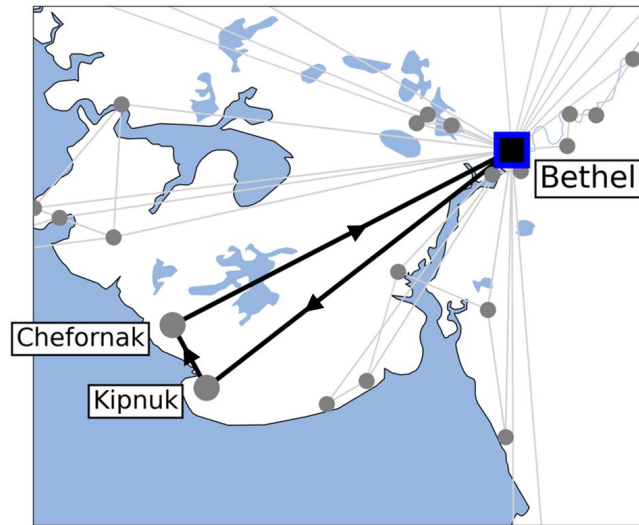


Figure 9. Bethel-Kipnuk-Cheforanak-Bethel is the busiest RAM route in the Bethel area, averaging 5-6 flights per day. Connections to some other villages are also shown.

Electric RAM airline operations in the Bethel area can use Bethel as a recharging hub, assuming an aircraft battery capacity of 1,833 kWh. This capacity is sufficient to fly the most demanding mission in the dataset plus a 45-minute loiter, consistent with night visual flight rules (VFR) reserve requirements. The outlying villages served by these flights do not require charging infrastructure. Aircraft recharging must occur simultaneously with passenger loading and unloading to avoid disrupting airline schedules because charging time is comparable to turnaround time.

A summary of our charging analysis results assuming a 30-minute turnaround is provided in Table 2. The maximum output power required to recharge all flights within 30 minutes (3.1 MW) is too high for cable-based fast charging. However, two pantograph-based fast chargers (each of which can typically charge at about 1-2 MW) may together be enough to meet the 3.1-MW requirement. Also, the peak airport power draw required to recharge all flights within 30 minutes (21 MW) exceeds the generating capacity of Bethel’s electrical grid (14.4 MW). The peak and average loads on Bethel’s grid in 2019 were even lower: 7.3 MW and 5.0 MW, respectively. New electric generation infrastructure is therefore needed to operate electric RAM flights with short turnarounds from Bethel, or changes to flight schedules are needed.

Table 2. Summary of charging results for a 30-minute turnaround.

Number of chargers	13
Max charger output power	3.10 MW
Max charging C-rate	1.69
Average grid power draw	2.08 MW
Peak grid power draw	21.0 MW

Number of chargers, charger power, and grid power (peak and average) as a function of turnaround time are shown in Figure 10 and Figure 11. These two figures show that turnaround time requirements must be carefully considered. Shorter turnarounds induce the following tradeoffs: reduced aircraft battery cycle life because of increased charging C-rates; fewer but more powerful chargers; and higher grid peak power draw, requiring more electrical ground infrastructure.

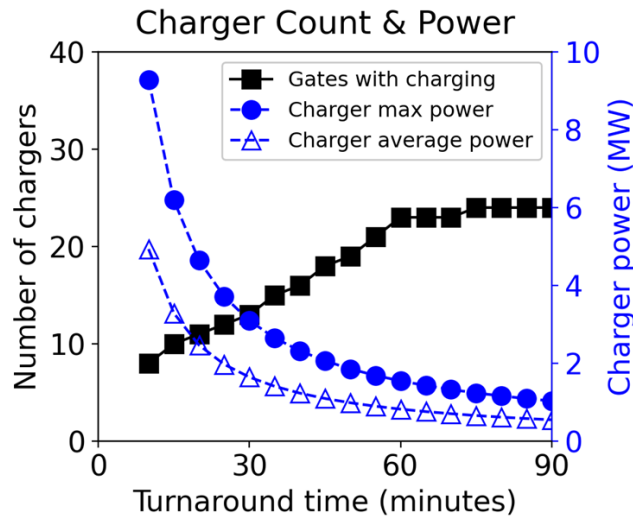


Figure 10. Number of chargers and charger power (average and maximum) as a function of turnaround time.

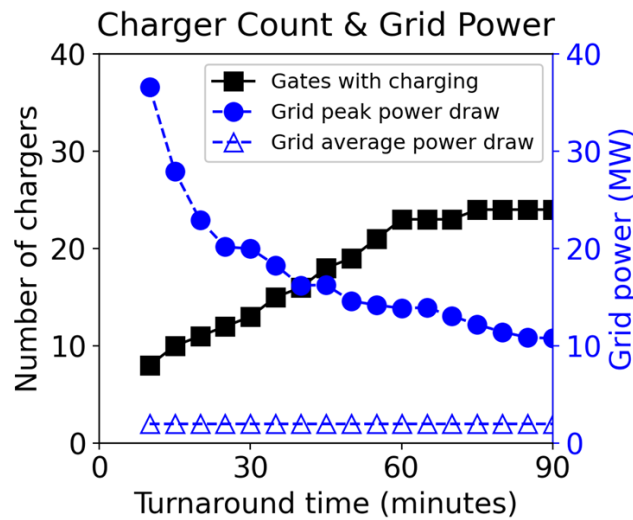


Figure 11. Number of chargers and grid power (average and maximum) as a function of turnaround time.

Electrical infrastructure (wind turbines, solar panels, and/or battery energy storage systems) to meet the charging loads for all flights was sized using NLR’s REopt tool. Results including installed distributed energy resources (DER), curtailment fractions (the fraction of electrical energy that is lost due to curtailment) and costs including up-front capital expenses (CapEx) and levelized cost of energy (LCOE) are provided in Table 3.



Table 3. Installed distributed energy resources (DERs), curtailment fractions, and cost estimates for different combinations of electrical infrastructure.

	Wind + battery	Solar + battery	Wind + solar + battery
Installed wind	41.0 MW	-	9.1 MW
Installed solar	-	178.6 MW	13.2 MW
Installed battery	144.4 MWh 21.8 MW	469.3 MWh 22.8 MW	79.9 MWh 21.6 MW
Wind curtailment	88.9%	-	69.3%
Solar curtailment	-	87.2%	32.1%
Upfront CapEx	\$458.8m	\$1840.4m	\$312.6m
LCOE (\$/kWh)	\$1.443	\$5.878	\$1.028

Table 3 shows that sizing, curtailment, and costs vary with the type of DERs selected: wind + battery, solar + battery, and wind + solar + battery. Solar + wind + battery is the least expensive option as measured by both upfront CapEx and LCOE. This is because solar and wind power were sized by different times of the year:

- The wind + battery case was sized by a period in late March/early April 2019 in which no wind was available for about 4 days, requiring a large and expensive battery to supply power. The wind turbines are oversized for the rest of the year as indicated by the curtailment fraction of 88.9% (i.e., almost 90% of the available wind energy on an annual basis was not used due to low demand).
- The solar + battery case was sized by a period in late December 2019 in which little light was available due to short day length, also requiring a large and expensive battery to supply power. The solar panels are oversized for the rest of the year as indicated by the curtailment fraction of 87.2%.
- The wind + solar + battery case is cheaper than either energy source alone because wind power is available when little solar power is available and vice versa. This is illustrated by the lower curtailment fractions: 69.3% and 32.1% for wind and solar, respectively.

The LCOE for the wind + solar + battery case was \$1.028/kWh. However, a typical commercial electricity price in Bethel in 2025 is only \$0.568/kWh; the new electrical infrastructure required for electric RAM flights is almost twice as expensive to operate as Bethel’s existing grid. Recall that electric RAM charging requires more power than the grid can provide. Therefore, further cost reductions may be necessary.

Publications

None.

Outreach Efforts

Dr. Brown gave a poster presentation at the 2024 ASCENT Fall meeting in Washington, D.C., and a slide-based presentation at the 2025 ASCENT Spring meeting in Knoxville, Tennessee, to disseminate the findings. Dr. Brown also gave a slide-based presentation at the Zero Impact Aviation Alliance meeting in May 2025, hosted at MIT.

Student Involvement

None.

Plans for Next Period

Over the coming reporting period, the team will elaborate on the Bethel, Alaska, case study. Specifically, we will refine our estimates for electrical infrastructure size and cost; we will also estimate the sensitivity to the turnaround time requirement. We will further assess options for reducing infrastructure costs, possibly including diesel generators and/or power curtailment to avoid having to oversize renewable electricity generating infrastructure. Finally, we will investigate ways of generalizing the results across additional airports.