Project 052 Comparative Assessment of Electrification Strategies for Aviation

Massachusetts Institute of Technology

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University Participants

Massachusetts Institute of Technology (MIT)

- PI: Professor Steven R. H. Barrett; Co-PIs: Dr. Florian Allroggen, Dr. Raymond Speth
- FAA Award Number: 13-C-AJFE-MIT, Amendment Nos. 062, 072, and 080
- Period of Performance: October 1, 2020 to September 30, 2021
- Tasks:
    1. Develop a suite of roadmaps for aircraft electrification (covered in the previous reporting period; 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 of electrification strategies
    4. Comparative validation runs (to be started in the following reporting period; not covered in the current reporting period)
    5. Analyze the system-level costs and benefits of the electrification strategies (to be started in following reporting periods; not covered in the current report)

Project Funding Level

This project received $600,000 of FAA funding and $600,000 of matching funds. The sources of matching funds were approximately $140,000 from MIT, plus third-party in-kind contributions of $460,000 from NuFuels LLC.

Investigation Team

PI:	Professor Steven Barrett (MIT) (all MIT tasks)
Co-PIs:	Dr. Florian Allroggen (MIT) (all MIT tasks)
	Dr. Raymond Speth (MIT) (Tasks 1, 2, and 4)
Co-investigator:	Dr. Sebastian Eastham (MIT Task 5)
Postdoctoral Associates:	Haofeng Xu (MIT, Tasks 2, 3, and 4)
	Christoph Falter (all MIT tasks)
Graduate Research Assistants:	Nicolas Gomez-Vega (MIT, Tasks 1, 2, and 4)
	James Abel (MIT Tasks 2 and 3)
	Dun Tan (MIT Task 2)

Project Overview

The long-term goal of this project is to quantify the costs, emissions, and resulting environmental impacts (i.e., climate and air-quality impacts) of different electrification approaches for commercial aviation. The electrification pathways considered range from battery-electric (or "all-electric") aircraft to electrofuel-powered and liquid hydrogen (LH_2)-powered aircraft, for which electrofuels and hydrogen are produced by using renewable electricity. The project will help identify the best approach for using one unit of electric energy to power aviation.

In the project, we analyze the costs, emissions, and atmospheric impacts associated with each electrification strategy. We develop both system-level engineering and system-level economic models, which include electricity generation, fuel production, transport 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. The models quantify differences in costs and emissions associated with each electrification approach, as compared with a set of baseline aircraft powered by conventional petroleum-derived fuels or drop-in sustainable aviation fuels (SAF). The outputs from these models will be used in a cost–benefit model, which will provide insights into the costs associated with each technology—both investment and operating cost—and compares them with the lifecycle climate and air-quality abatement potential. When comparing electrification scenarios with the conventional petroleum-derived baseline, we take various electricity production scenarios (e.g., different fossil fuels and renewables) into account.

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

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Objectives

The goal of this task is to develop an aircraft technology, production, and operation model, as well as a fuel production model. Jointly, these models provide a technical representation of the power conversion processes from the initial power generation to propulsion onboard the aircraft. These models provide a technical basis for the comparative assessments in this project.

During the reporting period, our analysis focused on defining the mass and energy balances, as well as key technologies for producing electrofuels, specifically drop-in power-to-liquid (PtL) fuels and LH_2. In addition, a modeling platform for estimating the production cost of aircraft was developed.

Research Approach

Modeling of PtL production

PtL fuel is modeled to be produced from water via electrolysis and from CO_2 captured either from the atmosphere via direct air capture or from waste CO_2 streams. Electricity is a major input to these processes; we assume that this electricity comes from renewable, low-carbon sources, such as wind and photovoltaics (PV). This assumption is based on prior analyses showing that most current grids do not allow PtL fuels to be produced with lower lifecycle greenhouse gas (GHG) emissions than petroleum-derived fuels, because of the high reliance on fossil fuels for power generation in many grids worldwide. PV and wind energy are low-emission sources of electricity that can be applied in many regions at relatively low cost. A main difference between these two renewable sources of electricity is their capacity factor, i.e., the share of full load hours per year: whereas PV is limited to capacity factors of up to about 35% (single-axis tracked modules in sunny regions), wind energy significantly surpasses this value in many regions.

For the purposes of this analysis, the fuel production processes rely on an electrolyzer to produce hydrogen. This hydrogen is used as a constituent of synthesis gas (H_2 + CO, syngas) and to reduce CO_2 to CO in the reverse water–gas shift reaction (RWGS). CO_2 for the process is assumed to be captured from the atmosphere with a temperature–pressure swing adsorption process. Direct air capture of CO_2 requires electricity and low-temperature heat. Because of the low temperatures required to regenerate the sorbent (~100 °C), the thermal energy input can be at least partly covered by waste heat from other process steps, such as Fischer–Tropsch synthesis. Syngas is converted into liquid fuels in the Fischer–Tropsch process, which produces hydrocarbons with different chain lengths, from methane to waxes. Aftertreatment increases the yield of jet fuel by adjusting the chain lengths to the desired range.

The transport of PtL fuels leverages the established infrastructure of oil pipelines, ships, and trucks.

The total energy demand of PtL production is estimated to be 2.6–3.1 MJ of electricity per MJ of fuel today and 2.2–2.6 MJ (electricity)/MJ (PtL) in the year 2050.

Modeling of LH_2 production

Similar to PtL fuel production, we model the LH_2 fuel production pathway to utilize electrolysis. Based on an extensive literature review, we assume that electrical energy is transported via high-voltage direct-current lines from the location of PV and wind power generation to the location of fuel production, which is often close to the airport. This method of energy distribution has been found to be favorable, given the difficulties in transporting hydrogen, especially in liquid form (i.e., low temperatures of LH_2 transport).

For the electrolysis, a proton-exchange membrane (PEM) electrolyzer is considered in the modeling, because of its responsiveness to changing electricity loads and its projected costs. The produced hydrogen is then liquefied via established processes (different pre-cooling steps and gas expansion).

The total energy demand for LH_2 production is estimated to be 1.8–2.2 MJ of electricity per MJ of LH_2 today and is expected to be within 1.4–1.7 MJ (electricity)/MJ (fuel) in the year 2050.

Aircraft cost model

Two models were developed to estimate the production cost of a novel aircraft design using non-drop-in fuels: one for the airframe and one for the propulsion system.

The airframe cost model is based on the Development and Procurement Costs of Aircraft (DAPCA) IV cost estimation model, as presented by Raymer. This model breaks down the cost of a new airframe into development, tooling, production, and flight-testing. The primary input to this model is a modified operating empty weight (OEW), and component weights are re-weighted according to their contribution to the overall cost of a typical airframe. Additional corrections are added to account for the higher research and development costs of aircraft using novel propulsion concepts.

The lack of established cost models for novel aircraft propulsion concepts (e.g., turboelectric systems and hydrogen-powered systems) necessitated the development of cost estimates from analogs in non-aerospace contexts. Cost models for electric motors and motor controllers in a turboelectric aircraft, for example, were scaled from estimates of the costs of these parts in industrial, automotive, and power-generating sectors. Similarly, the costs of fuel tanks for LH_2 (whose design drives many of the changes to the overall configuration of LH_2-fueled aircraft) was scaled from the costs of tanks currently used in LH_2 tanker trucks. Additional adjustment factors were added to the costs of these systems to account for the increased development costs for aerospace-compatible components.

Milestone
The modeling of fuel production pathways has been completed. The results have been presented to the International Civil Aviation Organization (ICAO) Committee on Aviation Environmental Protection (CAEP) Long-Term Aspirational Goal (LTAG) Task Group and are contributions to the final report of the LTAG fuel subgroup.

Major Accomplishments
MIT has developed models representing the physical and technical processes to produce PtL and LH_2 fuels under both current and future technologies.

The MIT team has used the methods and data developed under this effort to provide scientific input to ICAO's development of a LTAG for decarbonizing the aviation sector.

Publications
None

Outreach Efforts
- The team summarized the fuel production modeling during the Fall 2020 and Spring 2021 ASCENT meetings.
- The team gave multiple presentations to ICAO's LTAG Task Group and actively participated in numerous expert discussions.
- Presentation at the Cryogenic Engineering Conference and International Cryogenic Materials Conference (CEC-ICMC) on the use of hydrogen to reduce the carbon footprint of aviation.
- Presentation to the Aviation Emissions Characterization (AEC) Meeting, April 2021.
- Presentation to numerous stakeholders, including NASA, Advanced Research Projects Agency–Energy (ARPA-E), and industry.

Awards
None

Student Involvement
During the reporting period, the MIT graduate students involved in this task were Nicolas Gomez Vega, James Abel, and Dun Tan.

Plans for Next Period
Over the coming year, the team will expand the existing capabilities of the aircraft design tool TASOPT, which are currently limited to A320-class aircraft powered by drop-in fuels and batteries. In particular, the team will work to implement a hydrogen aircraft in TASOPT.

In addition, the current aircraft implementations in TASOPT are limited to single-aisle aircraft for medium-haul routes. The team will ramp up work on including aircraft models with longer or shorter ranges, as well as higher or lower passenger capacity.

Task 3 - Develop a Model for Analyzing the Economics and Emissions of Electrification Strategies
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Objective(s)
The goal of this task is to develop a system-level analysis capability for assessing the possible electrification pathways (e.g., battery electric, or hydrogen fuel cell) and their deployment in various aircraft electrification scenarios (e.g., replacing regional flights below 1,000 nmi at a specific airport). The system model focuses on the processes upstream of the fueling, by using the fuel production model as outlined under Task 2, and on the operation of the aircraft itself. Outcomes of interest include the operating costs, required investments, and lifecycle GHG emissions of the system.

During the current period, the focus of the team was: (a) to quantify the energy system interactions of scaling up PtL and LH_2 production; (b) to quantify the environmental footprint and economics (cost and investment pathways) of LH_2 and PtL production; and (c) to outline and assess the LH_2 distribution infrastructure at airports.

Research Approach

Energy system implications of scaling up PtL or LH_2 production

As shown under Task 1, the production of LH_2 or PtL fuel requires substantial amounts of electricity, because of the energy intensity of electrolysis, the capture of CO_2, and the liquefaction of hydrogen. The implications of fuel replacement on the power generation sector are shown below in a case study of the Paris Charles de Gaulle airport (CDG). We note that the energy efficiency of hydrogen-powered aircraft is assumed to be identical to that of the current aircraft using Jet-A fuel.

If all fuel at CDG in 2019 were to be replaced by LH_2, and the fuel efficiency of LH_2 aircraft were the same as that of conventional aircraft, 8.4 GW of annually averaged electrical power generation would be required to produce the required LH_2 (Figure 1). Most of the energy would be used for water electrolysis. Replacing all fuel with PtL would require even more power generation – between 10 and 17 GW annually averaged, depending on the assumed technology standard. It should be noted that in the calculations, only the electricity attributable to the jet fuel fraction is counted; the power generation for the entire output slate leading to the required jet fuel production is significantly larger. The numbers reported for the jet fuel share compare to a total installed power generation capacity in the French grid of 130 GW (nameplate capacity) and of 7 GW for the largest nuclear power plant in the world (nameplate capacity). Taking the intermittency of renewable power generation into account, the required area for solar-PV-based power generation for LH_2 would be >585 km^2 if LH_2 is produced completely remotely (production and liquefaction) in a solar-optimal location, and >490 km^2 for offsite H_2 production plus >130 km^2 for onsite local liquefaction. If PtL were used, more than 700 km^2 of land would be required (offsite) to run PtL fuel production for CDG.

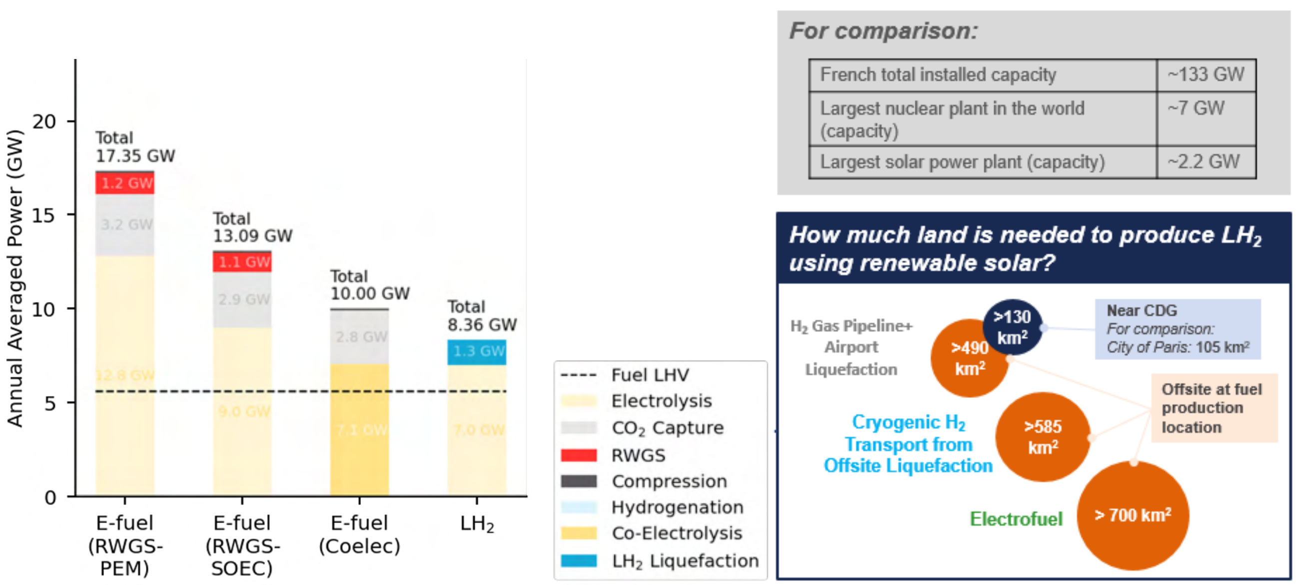

Figure 1. Energy system implications of supplying Paris Charles-de-Gaulle airport with LH_2 or PtL.

It is important to note that CDG is not an exception. Figure 2 shows the annually averaged electrical power generation requirements for full LH_2 replacement at the 20 airports with the highest energy demand, on the basis of the traffic in 2019. The largest power generation requirement is found for London Heathrow, with 12.8 GW (annually averaged). However, if hydrogen were (hypothetically) used only for flights shorter than 2,000 nmi, the power requirements would decrease to 1.5 GW. This strong sensitivity to flight length is unique to London Heathrow. For example, for the Atlanta airport, we find that replacement for flights shorter than 2,000 nmi would require electric power generation at 4.0 GW (annually averaged), whereas full replacement for all flights would require 5.6 GW (annually averaged).

If all airports were served with LH_2 at 2019 traffic levels, 536 GW of power generation (annually averaged) would be required. This requirement would increase to 640–1,113 GW in the case of PtL, depending on technological progress in the energy intensity for PtL production (Figure 3). For comparison, the estimated global PV power generation capacity (nameplate) is approximately 950 GW (end of 2021), and the total power generation capacity in the US grid is approximately 1,200 GW. However, the number should also be considered in the context of future scale-up of renewable power generation, e.g., as modeled in the International Energy Agency's Sustainable Development Scenario, which assumes a global annually averaged power generation from PV and wind of 3,000 GW by the year 2050.

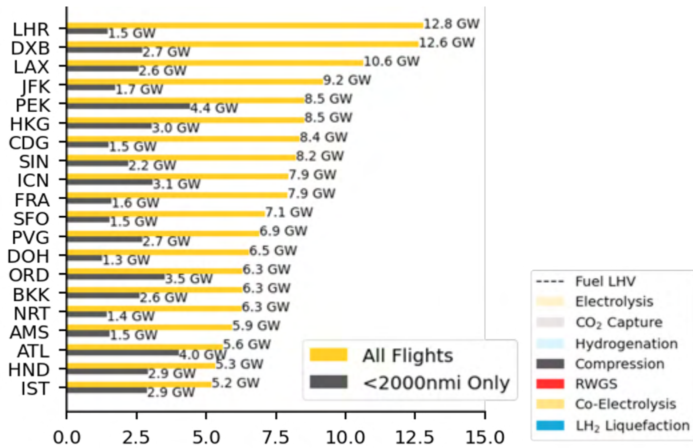

Figure 2. Energy system implications of replacing jet fuel with LH_2 at the 20 airports with the highest energy intensity (according to 2019 traffic).

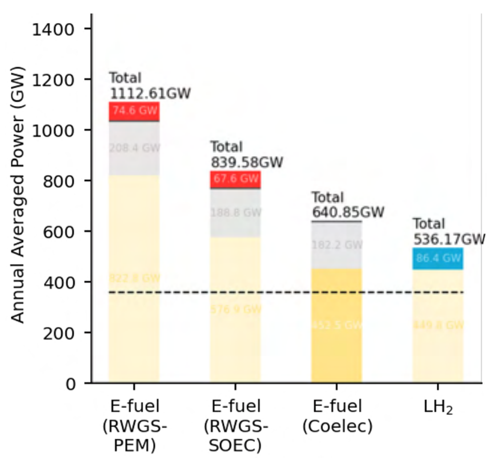

Figure 3. Energy system implications of replacing jet fuel with either LH_2 or PtL in a global replacement scenario (according to 2019 traffic).

Environmental and economic footprints of LH_2 and PtL

The production costs for PtL are estimated in three scenarios of different ambition regarding the transition speed to a renewable energy base. In Figure 4, the minimum selling price of PtL, as calculated in a joint effort with researchers from Washington State University, is shown for the three scenarios in the timeframe from 2020 to 2050. Today, the production costs for PtL fuel production using waste CO_2 are estimated to be in the range of 2.8–4.6 $/L in the most ambitious scenarios. In the least ambitious scenario, the costs are estimated to be in the range 3.4–6.2 $/L. These costs are expected to decrease to 1.3–1.7 $/L and 1.8–3.0 $/L in the most and least ambitious scenarios, respectively.

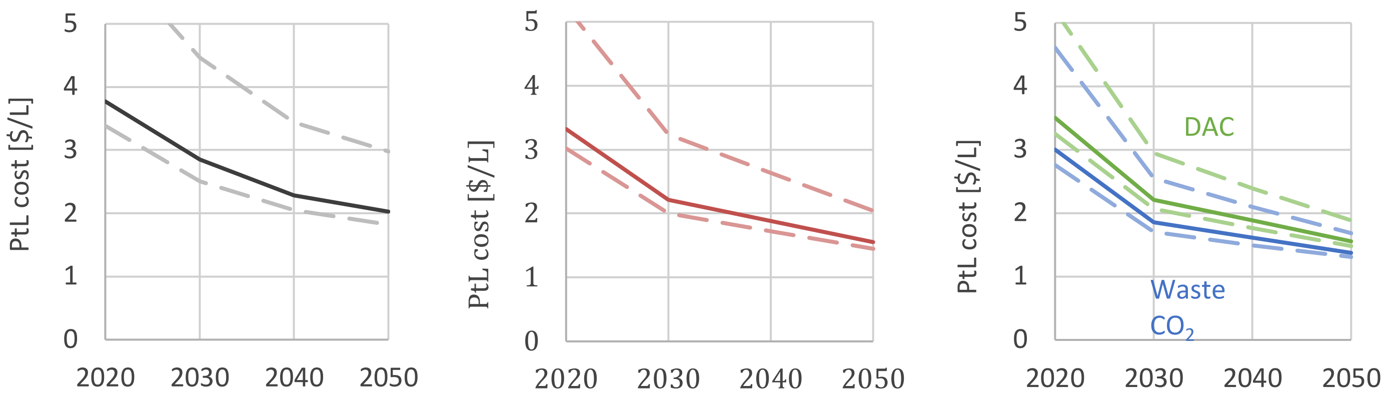

Figure 4. Minimum selling price of PtL for three integrated scenarios reflecting different levels of ambition in the transition to a renewable energy base (left: least ambitious; middle: average scenario; right: most ambitious). Solid lines show the median scenario, and dotted lines show the minimum and maximum estimates. DAC=direct air capture.

The production cost projections for LH_2 are shown in Figure 5. The expected minimum selling price today is in the range of 6–13 $/kg (or 2.0–4.8 $/L of jet fuel equivalent). These costs are expected to decrease to the range of 1.9–4.9 $/kg (or 0.5–1.4 $/kg of jet fuel equivalent) in 2050, mainly driven by cost reductions and efficiency gains in water electrolysis and hydrogen liquefaction. At the lower end, the cost estimates in 2050 approximately reach cost parity with conventional jet fuel at today's market prices.

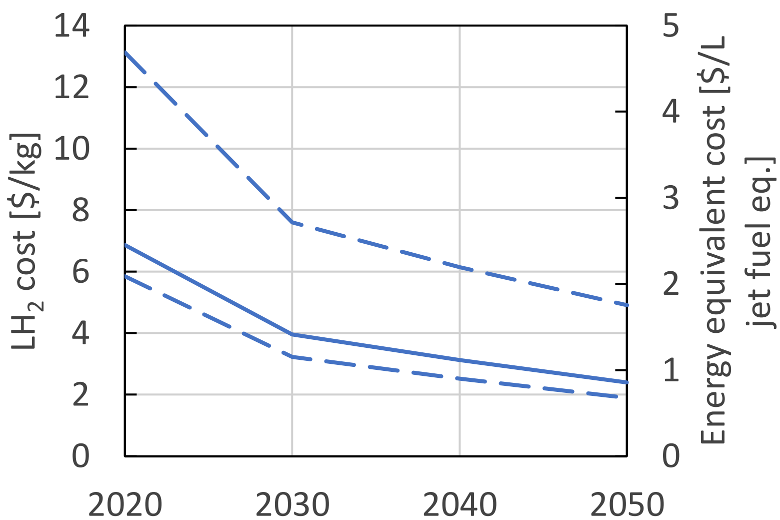

Figure 5. Minimum selling price of LH_2 fuel. Minimum, average, and maximum estimates are indicated.

The use of renewable energy for producing alternative fuels has the potential to reduce the lifecycle GHG emissions associated with LH_2 and PtL. In Figure 6, the GHG emissions of PtL fuel production are shown from 2020 to 2050 for three scenarios with different level of ambition regarding the introduction of renewable energy. Embedded emissions are taken into account, which raises the specific emissions per megajoule of fuel above zero. The resulting emissions of PtL fuel using a mix of PV and wind energy are on the order of 10–20 g/MJ, whereas wind achieves significantly lower emissions than PV. If the electricity for PtL production is assumed to come from the grid (at the global grid average), PtL fuels currently do not provide an emissions benefit over conventional jet fuel (conventional jet fuel carbon intensity at 89 gCO_2e/MJ). This finding changes only under ambitious grid decarbonization scenarios.

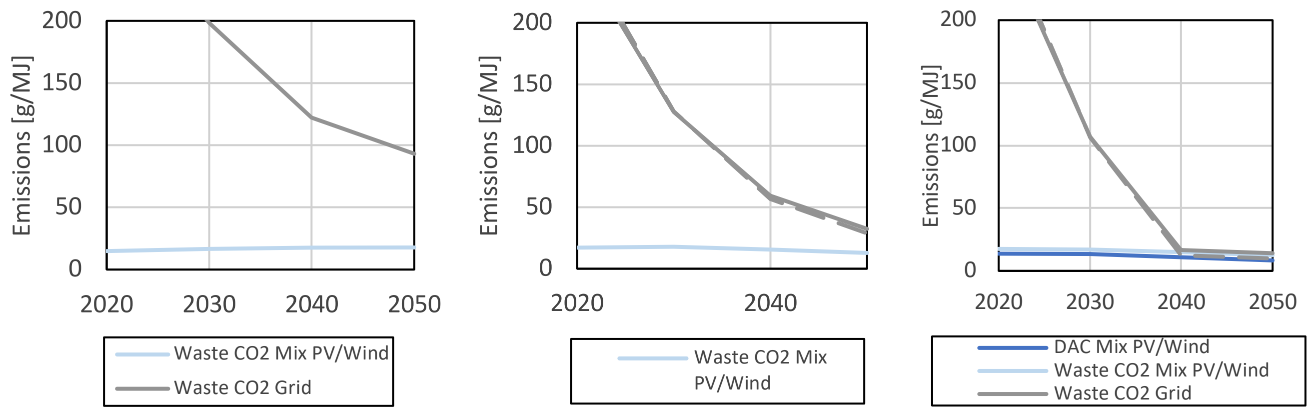

Figure 6. Emission trajectories of PtL production for three integrated scenarios reflecting different levels of ambition in the transition to a renewable energy base (left: least ambitious; middle: average scenario; right: most ambitious). Either waste CO_2 or atmospheric CO_2 is used for the production of PtL.

The GHG emissions of LH_2 production are shown in Figure 7 for both grid electricity and a mix of PV and wind energy. Similar to PtL, the use of renewable energy is required to achieve a significant reduction of GHG emissions relative to fossil fuels. If PV/wind energy is exclusively used for LH_2 production, lifecycle GHG emissions of 6–10 g CO_2e/MJ can be reached, while considering embedded emissions. Under ambitious global grid decarbonization, as modeled in the International Energy Agency Net Zero Emissions 2050 scenario, LH_2 could provide GHG emissions savings over conventional jet fuel from the late 2020s, if the global grid average is assumed.

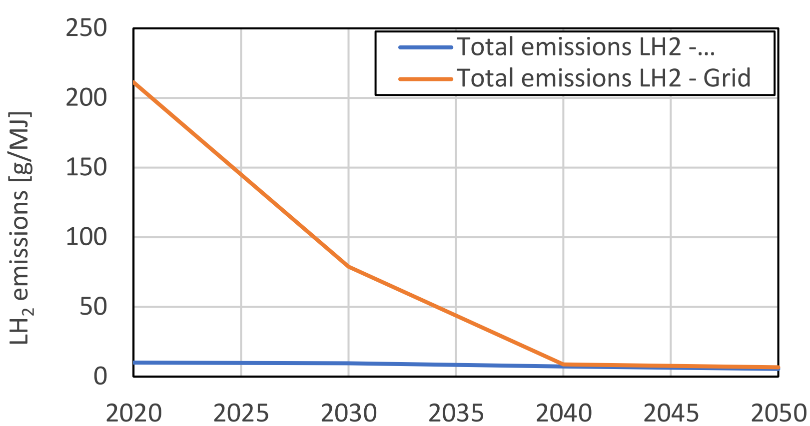

Figure 7. Lifecycle GHG emissions of LH_2 production assuming ambitious grid decarbonization.

LH_2 distribution infrastructure at airports

Because LH_2 is a non-drop-in fuel, new airport infrastructure would be required for fuel distribution. We therefore determined the scale of the required investments. To estimate this cost, three potential refueling strategies for LH_2 aircraft were analyzed: (a) using tanker trucks to deliver fuel to aircraft at the gate, (b) using an underground hydrant system to deliver fuel to the gate, and (c) moving aircraft to a remote bay closer to the fuel storage farm for refueling. The scale of each of these systems was assessed by using flight schedule data to estimate energy demand, and information regarding airport layouts (e.g., locations of gates) to estimate the physical size of the infrastructure required (e.g., the length of refueling pipelines). After the refueling system was sized, its cost was calculated with a parametric cost model. This model was used to calculate capital and operating costs of a potential LH_2 refueling system (e.g., trucks, pipelines, storage tanks, labor, etc.) for each global airport and to estimate the additional land required for this system. Cost assumptions were derived from an extensive literature study and were largely rely on the extrapolation of values from existing hydrogen systems used in other industries (e.g., automotive and spaceflight). In addition, the model explicitly considers the unique physical properties of hydrogen infrastructure, such as the requirement to install hydrogen pipelines in open trenches for safety.

No single refueling strategy was found to be optimal. Instead, the optimal infrastructure setup varied depending on the geometric layout and demand profile of each airport. In general, airports with expansive layouts favored truck-based refueling systems, because the large distances between fuel storage infrastructure and gates would make hydrant-based systems uneconomical. In contrast, more compact airports with frequent movements favor hydrant-based systems. These trends are illustrated in the two case studies shown in Figure 8: the expansive multi-terminal layout of Kuala Lumpur Airport and the more compact layout of Helsinki Airport.

In many cases, the greatest additional cost imposed by hydrogen refueling was found to be from the lost revenue resulting from longer aircraft turnaround times. Longer fueling times are potentially caused by LH_2's lower volumetric energy density as compared to conventional jet fuel, if flow rates in hydrogen refueling hoses are comparable to those achieved by existing conventional fuel hoses. The extent to which longer fueling times affect turnaround times depends on (a) the flight distance and required fuel volume, and (b) the ground operations that can safely be carried out in parallel with refueling (e.g., boarding/de-boarding). The analysis shows that, for most short-haul flights, the additional refueling time falls within the existing turnaround-time window, even if boarding and loading cannot commence during fueling. With increasing flight distances, these restrictions become more binding and can lead to significant increases in turnaround times.

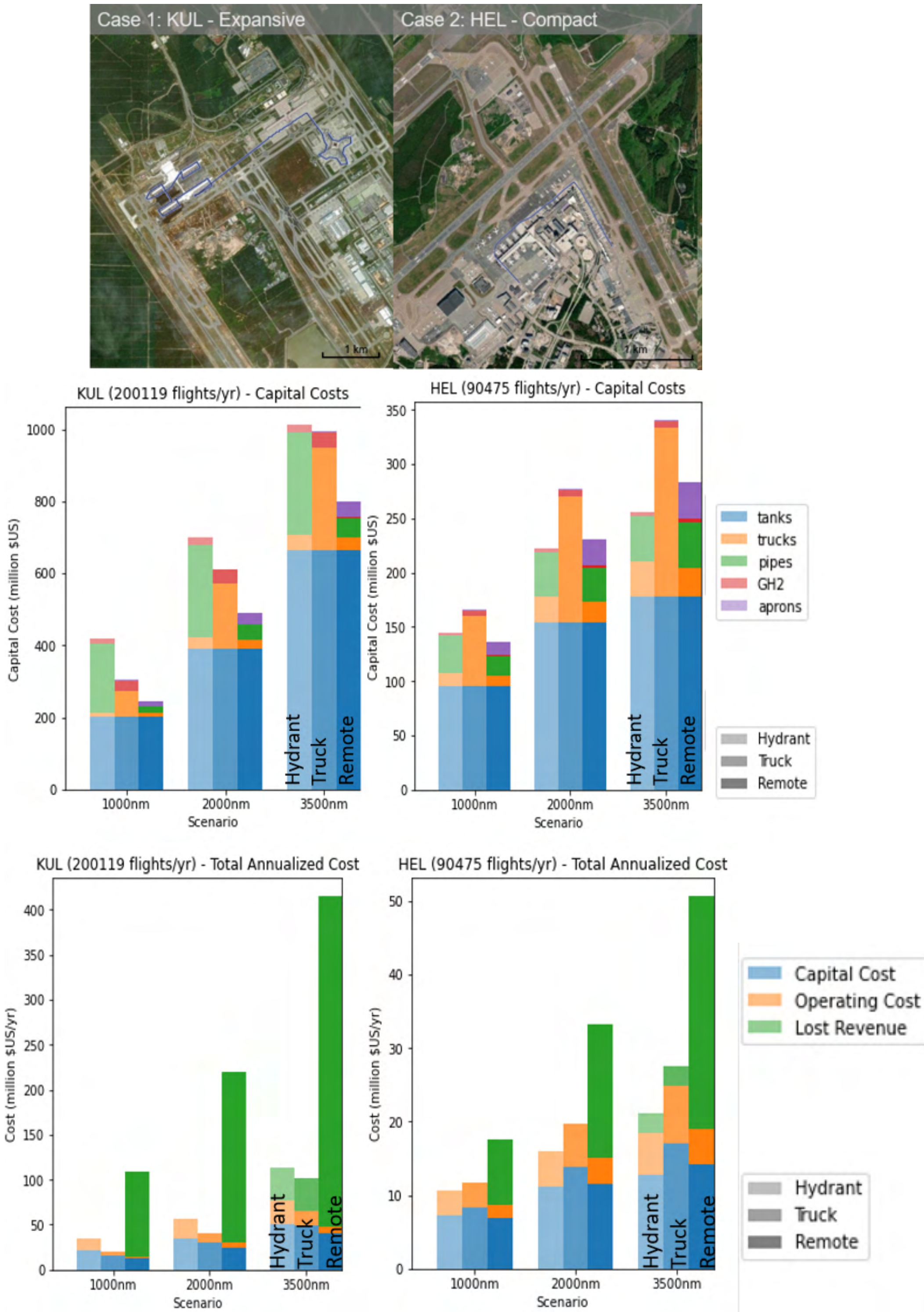

Figure 8. LH_2 airport distribution infrastructure case studies for Kuala Lumpur Airport (left) and Helsinki Airport (right), showing terminal layout (top), system CapEx (middle), and yearly annualized costs (bottom).

Milestones
The system-level modeling of fuel production and distribution has been completed for LH_2 and PtL. The results have been presented to ICAO CAEP's Long-Term Aspirational Goal (LTAG) Task Group and form the basis for the final report of LTAG's fuel subgroup.

Major Accomplishments
The team has compiled a full modeling chain for evaluating the production and distribution of PtL and LH_2 at scale.

The results from this research provide scientific input for the development of an LTAG for decarbonizing the aviation sector.

Publications
None

Outreach Efforts
- The team summarized key findings during the Fall 2020 and Spring 2021 ASCENT meetings.
- The team gave multiple presentations to ICAO's LTAG Task Group and actively participated in numerous expert discussions.
- Presentation to the CEC/ICMC Conference on the use of hydrogen to reduce the carbon footprint of aviation.
- Presentation to the Aviation Emissions Characterization (AEC) Meeting, April 2021.
- Presentation to numerous stakeholders, including NASA, ARPA-E, and industry.

Awards
None

Student Involvement
During the reporting period, the MIT graduate students involved in this task were Nicolas Gomez Vega and James Abel.

Plans for Next Period
The next step is to integrate the fuel production and distribution models with more detailed aircraft models, which are developed under Task 2. This integration will allow the team to consider additional feedbacks of energy carrier choice on the specific energy consumption of the aircraft and subsequently on the entire system.