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PERFORMANCE ANALYSIS OF FUEL CELL RETROFIT AIRCRAFT

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EXECUTIVE SUMMARY

The idea of powering aircraft with hydrogen fuel cells is gaining attention as a potential zero-emission solution for aviation. Retrofitting an existing aircraft with hydrogen fuel cell propulsion could mean zero-emission flying without having to develop a new aircraft from scratch. While fuel cells cannot yet produce enough power to propel narrowbody aircraft, they can power regional turboprop aircraft. This analysis models a retrofit ATR 72 turboprop aircraft with fuel cell propulsion and hydrogen storage and considers both liquid hydrogen (LH_2) and compressed gaseous hydrogen (GH_2) fueling options.

The size of hydrogen storage tanks necessitates their carriage inside the fuselage (reducing passenger capacity). Each row of removed seats is replaced with two vertically stacked cylindrical hydrogen tanks. Carrying more hydrogen increases an aircraft's maximum range while reducing its passenger capacity. This study simulates retrofits with passenger capacities from 42–70. Figure ES 1 illustrates the tradeoff between assumed passenger capacity and simulated range and energy intensity. The performance of reference aircraft, the ATR 72 and the Dash 8 Q300 (a smaller capacity turboprop aircraft), are included for comparison. While fuel cell retrofit aircraft cannot match the payload and range capabilities of fossil-fueled aircraft, they are more energy efficient, requiring fewer megajoules per available seat kilometer (MJ/ASK). Using LH_2 instead of GH_2 increases an aircraft's range and reduces its energy intensity.

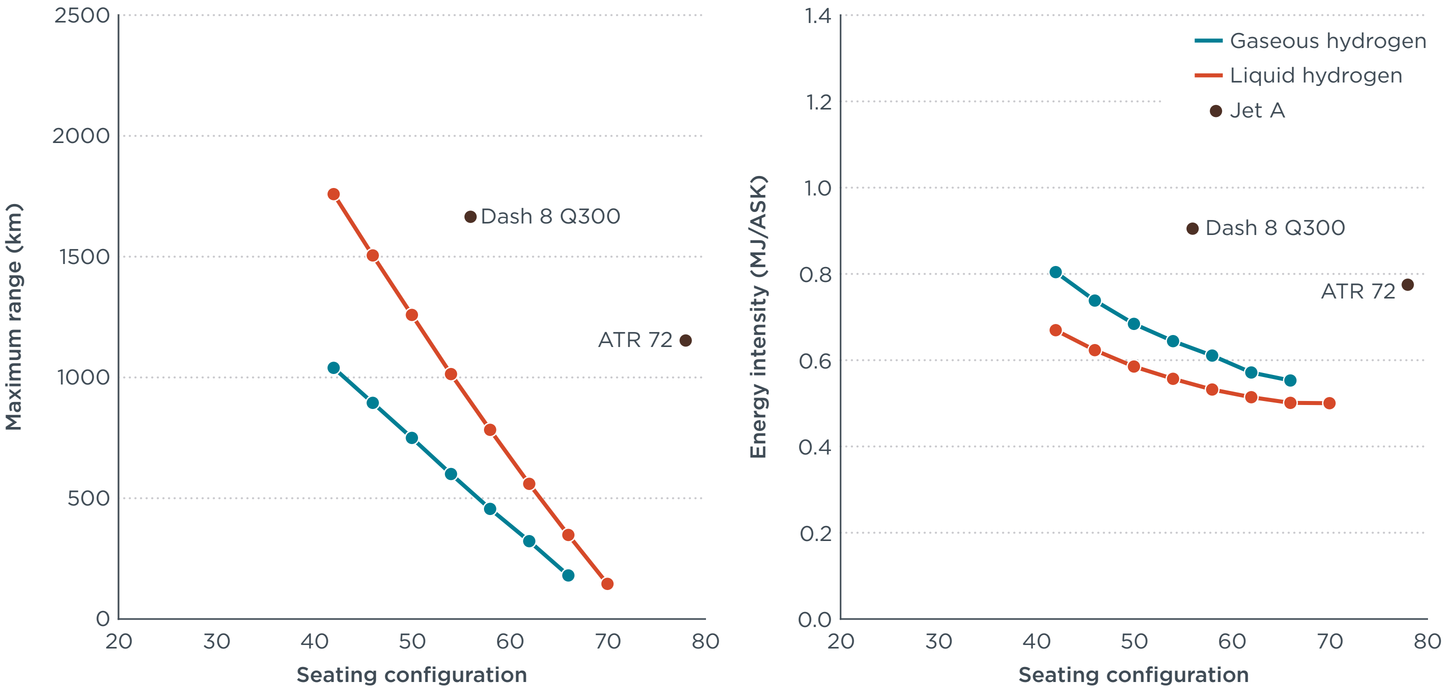

Figure ES 1. Maximum range (left) and energy intensity (right) of a fuel cell retrofit aircraft.

Comparing the payload-range capability of an aircraft to the turboprop routes flown in 2019 reveals that a 50-seat GH_2-powered aircraft and a 58-seat LH_2-powered aircraft could service 14% and 16% of turboprop ASKs, representing about 0.1% of commercial aviation's global ASK. While these cannot carry the 78 passengers an ATR 72 can, both hydrogen powered variants have a range longer than the length of 90% of all routes flown by ATR 72s in 2019. This study uses flights of 400 km and 700 km to simulate the real-world use of ATR 72s. These are roughly the distances from New York City to Washington D.C. and from Berlin to Brussels, respectively. These distances represent the median and 90^{th} percentile distances of the routes flown by ATR 72s. On such flights, fuel cell aircraft have lower energy and carbon intensities but are marginally more expensive to fuel. Retrofitting one ATR 72 that operates four daily 400-km flights 300 days each year, with fuel cell propulsion and fueled with green hydrogen, could reduce GHG emissions by 2,500 tonnes per year. This estimate includes the carbon intensity of fuel cell manufacturing.

A fuels analysis quantifies the carbon intensity and cost of fueling a retrofit aircraft with GH_2 and LH_2 with those for fueling an original ATR 72 with regular jet fuel (Jet A) and e-kerosene. This study also includes the lifecycle emissions and cost of producing a fuel cell and hydrogen storage, both of which must be replaced multiple times in an aircraft's lifetime. A fuel cell aircraft, fueled by green liquid hydrogen, can reduce carbon intensity by 88% compared to Jet A and by 35% compared to e-kerosene (see Figure ES 2).

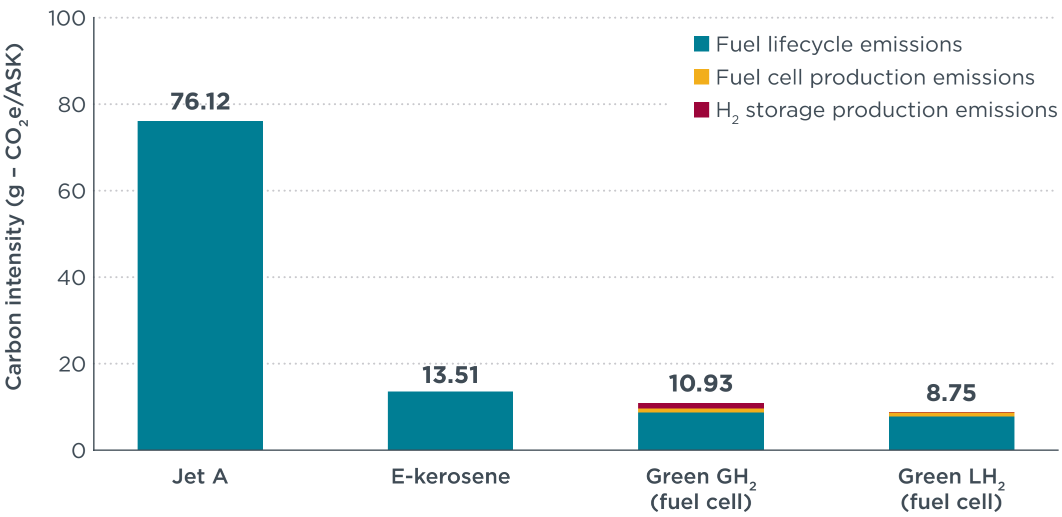

Figure ES 2. Carbon intensity of the different fueling options.

While green hydrogen will likely be more expensive than jet fuel in most cases, the increased efficiency of the fuel cell propulsion system would bring the price premium down to 29–40% in the United States in 2030 and would make fueling with green hydrogen cheaper than fossil jet fuel in the United States in 2050. In the European Union, where hydrogen is expected to be more expensive to produce, the price premium for using green hydrogen would be around 100% in 2030, dropping to 50% in 2050. Green hydrogen would be cheaper than e-kerosene in all cases.

In summary, a fossil-fueled turboprop aircraft retrofitted with hydrogen storage and fuel cell propulsion is more energy efficient and less carbon intensive, but more expensive to fuel. It would have lower payload and range capabilities but would reduce GHG emissions by 88% relative to the original aircraft.

TABLE OF CONTENTS

Executive summary i

List of abbreviations vi

Introduction 1

Methods 3

Fuel cells 3

Fuel cell parameters 3

Electric motors 4

Reference aircraft 5

Aircraft retrofitting 6

Reference mission simulations 10

Fuel analysis 10

Results 14

Range comparison 14

Payload and fuel storage optimization 15

Reference mission simulations 17

GHG mitigation potential 18

Fuels analysis 19

Sensitivity Analysis 20

Conclusions 22

Policy recommendations 24

References 25

Appendix A: Reference aircraft selection 28

Appendix B: Aircraft mission profile 29

Appendix C: Hydrogen cost estimation 30

LIST OF FIGURES

Figure ES 1. Maximum range (left) and energy intensity (right) of a fuel cell retrofit aircraft i

Figure ES 2. Carbon intensity of the different fueling options ii

Figure 1. Schematic of a fuel cell system 3

Figure 2. Comparison of the nacelle sizes. 6

Figure 3. Illustrative tank layout of a retrofitted ATR 72 for 50 passengers. 7

Figure 4. Fuel carbon intensities 11

Figure 5. Pump price of hydrogen in the United States in 2022 USD. 12

Figure 6. Pump price of hydrogen in the European Union in 2022 USD. 13

Figure 7. Fuel costs in 2022 USD by region and year. 13

Figure 8. Maximum range (left) and energy intensity (right) of the fuel cell retrofit aircraft. 14

Figure 9. Turboprop routes flown in 2019 compared to the payload-range capability of fuel cell aircraft retrofits. 16

Figure 10. Carbon intensity of different fueling options 19

Figure 11. Fueling costs for turboprop aircraft by fuel, 2022 USD. 20

Figure 12. Sensitivity analysis of aircraft range. Top: GH_2 aircraft with 50 passengers. Bottom: LH_2 aircraft with 58 passengers. 21

Figure A1. Utilization rate over the hydrogen refueling station lifetime 32

LIST OF TABLES

Table 1. Range of system-level fuel cell parameters used in the analysis.............................. 4

Table 4. Thermodynamic properties of Jet A, GH_2 and LH_2...7

Table 5. Hydrogen storage tank dimensions 7

Table 6. Range of hydrogen storage parameters used in the analysis 8

Table 7. Turboprop route coverage for each fuel cell aircraft scenario................................17

Table 8. Weights, range, and energy intensities of the turboprop aircraft.........................17

Table 9. Energy and emissions intensity of turboprop aircraft 18

Table A1. Relevant technical specifications of the ATR 72 and Dash 8 Q400..................28

Table A2. 2019 operations data for the ATR 72 and Dash 8 Q400.......................................28

Table A3. Estimate of green hydrogen production cost in 2020 USD per kg of hydrogen.. 30

Table A4. Estimated annual renewable energy price in the United States and EU in 2020 USD per MWh 30

Table A5. Estimated initial capital investment required for a 2,000 kg/day hydrogen refueling station in 2020 USD...31

Table A6. Financial assumptions for hydrogen refueling stations...32

LIST OF ABBREVIATIONS

ASK	Available seat kilometer
BoP	Balance of plant
CO_2	Carbon dioxide
DAC	Direct air capture
DOE	Department of Energy
gCO_2e	Grams of carbon dioxide equivalents
GH_2	Gaseous hydrogen
GHG	Greenhouse gas
GI	Gravimetric index
H_2	Hydrogen
ICCT	International Council on Clean Transportation
LH_2	Liquid hydrogen
MJ	Megajoule
MTOM	Maximum takeoff mass
PEMFC	Proton exchange membrane fuel cell

INTRODUCTION

Zero emission alternatives for commercial aviation are not currently available. Barring breakthroughs in battery energy storage, battery electric airplanes will be limited to use on short commuter flights with low passenger capacity (Mukhopadhaya, 2022; Mukhopadhaya & Graver, 2022). Similarly, while hydrogen combustion aircraft could service one-third of the commercial aviation market, they are unlikely to enter service before 2035 and their adoption would require large-scale hydrogen infrastructure (Mukhopadhaya & Rutherford, 2022). On the other hand, hydrogen fuel cell powered aircraft will likely be available before 2030 and require less hydrogen infrastructure due to their smaller size and hydrogen consumption. Consequently, they could also be used as a testbed for hydrogen infrastructure at airports.

Several companies are currently developing fuel cell aircraft. For example, Project Fresson, led by Cranfield Aerospace Solutions and funded by UK Research and Innovation (UKRI), is converting a 9-seat Britten-Norman Islander aircraft to electric propulsion (UKRI, 2019). The project pivoted from battery power to fuel cells in May 2021 (Perry, 2022). H2FLY became the first company to fly a fuel cell powered aircraft, the HY4, between two airports and the first to fly it above 7,000 feet (H2FLY, 2022). ZeroAvia and Universal Hydrogen are developing fuel cell retrofits for existing turboprop aircraft (Universal Hydrogen, 2023.; ZeroAvia, 2023). While ZeroAvia is taking a tiered approach, starting by retrofitting a 10–20-seat aircraft and planning to retrofit a 40–80-seat aircraft in the future, Universal Hydrogen is developing a conversion kit for larger turboprops like the ATR 72 and the De Havilland Canada Dash-8 Q300. Both ZeroAvia and Universal Hydrogen have flight tested aircraft with one hydrogen fuel cell engine (Gallucci, 2023a, 2023b). Airbus also revealed it is developing a fuel cell propulsion system in addition to its hydrogen combustion engines under its ZEROe initiative to develop hydrogen powered commercial aircraft (Airbus, 2022).

In addition to these practical projects, there is a sizeable body of literature on fuel cell use in aviation. Some studies have focused on providing detailed design parameters for fuel cell systems that would be required to power aircraft of varying sizes (Datta, 2021; Kadyk et al., 2018). Other studies delve into the conceptual design of fuel cell powered general aviation and commuter aircraft and detail key aircraft performance metrics (Nicolay et al., 2021; Vonhoff, 2021). These aircraft are smaller, carrying ten or fewer passengers, rather than the 40–70 considered for the retrofit in this study. Relatedly, bigger fuel cell concepts have also been explored, and there are efforts to develop fuel cell powered concept aircraft. For example, the FlyZero project, funded in part by the government of the United Kingdom, developed three aircraft concepts; the smallest was a fuel cell powered regional aircraft that could carry 75 passengers a maximum of 1500 km (Debney et al., 2022). A similar study by McKinsey yielded two fuel cell powered aircraft: a 19-seat variant with a range of 500 km and an 80-seat variant with a range of 1,000 km (McKinsey & Company, 2020).

Those studies developed new aircraft designs around fuel cell propulsion tailored to address the challenges of hydrogen storage and utilize the advantages of electric propulsion. They did not consider retrofitting existing aircraft with fuel cell propulsion. Accordingly, this study fills that gap and evaluates the performance of a regional aircraft retrofit with a fuel cell propulsion system and modular hydrogen storage. It also considers both compressed gaseous hydrogen (GH_2) and liquid hydrogen (LH_2) as fuel choices.

With the focus on retrofit aircraft, the conceptual design of a new aircraft is out of the scope of this study. Instead, this study focuses on quantifying the costs associated with hydrogen production, processing, and refuelling along with the cost of producing fuel cells and on-board hydrogen storage (both of which will need regular replacement during an aircraft's lifetime). While this study also quantifies the life cycle greenhouse gas (GHG) emissions of fuel production and fuel cell manufacturing, it does not include a life cycle GHG assessment of the aircraft itself over its entire lifetime. Additionally, the impact of short-lived climate pollutants, such as contrail/cirrus formation, is not quantified.

This analysis first introduces hydrogen fuel cells, electric motors, and the parameters used to estimate their performance. This is followed by the description of the reference aircraft, the aircraft retrofitting process, the performance analysis, and the fuels considered. Next, the study presents the payload-range capability of a potential fuel cell aircraft and how much of the current aviation market it may address. The fuels analysis is presented next with a focus on GHG intensity and fuel costs. The results are capped by a sensitivity analysis of aircraft range to the modelling parameters. This study ends with a discussion of the results, thoughts on future work, and policy recommendations.

METHODS

FUEL CELLS

Reacting hydrogen and oxygen to form water releases significant energy. Hydrogen fuel cells harness the energy released in this chemical reaction to generate electricity. There are a few different architectures of fuel cells. The proton exchange membrane fuel cell (PEMFC) is the prevalent architecture in road vehicles and the likely one to power aviation (Datta, 2021).

Previous ICCT research describes PEMFC technology in its application to long-haul trucking (Basma & Rodríguez, 2022). However, to clarify terminology, it is helpful to describe the different parts of the fuel cell system (as illustrated in Figure 1).

An individual **fuel cell unit** refers to a single set of catalyst electrodes, electrolyte, and gas delivery layers that can produce electricity by harnessing the energy released when hydrogen and oxygen combine to form water.

Individual fuel cell units cannot produce much power, so they need to be combined to generate enough electricity to run transportation vehicles. Accordingly, hundreds of fuel cell units are put together to form a **fuel cell stack.**

Operating a fuel cell safely and reliably requires auxiliary systems in addition to the stack. These additional systems are referred to as the **balance of plant** (BoP) and include thermal management, gas delivery, water exhaust, and electrical systems.

Putting together the fuel cell stack and BoP creates the **fuel cell system**. This is a complete electricity generation machine that can be placed in a transport vehicle. It does not include hydrogen storage tanks.

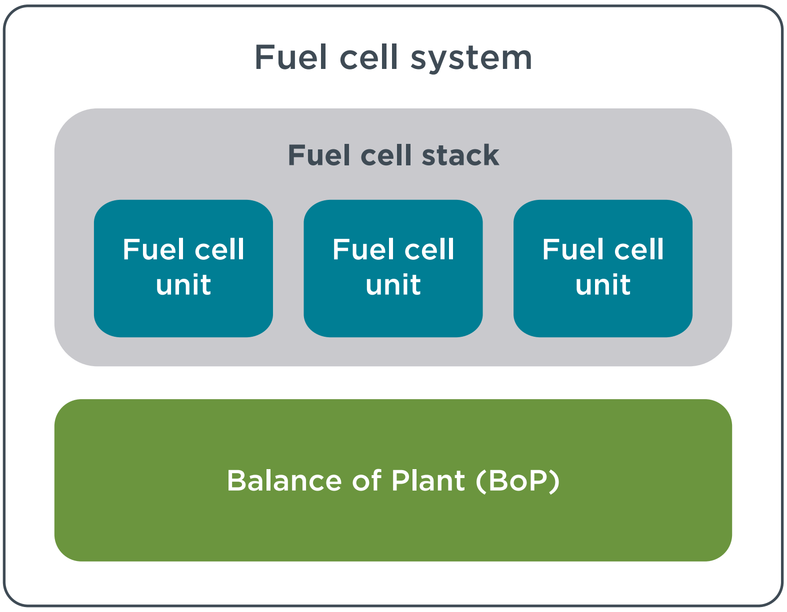

Figure 1. Schematic of a fuel cell system.

FUEL CELL PARAMETERS

This work investigates a range of values for fuel cell parameters to calculate the sensitivity of aircraft performance to them. Table 1 lists the low, central, and high values for each parameter. Central values are higher than the values reported in the review of the state of the art of automotive fuel cell technology in 2020 (Padgett & Kleen, 2020). This is based on input from industry experts and on the fact that fuel cell technology will have several years to mature before being used in these prospective aircraft.

Furthermore, aircraft fuel cells will need to output around 50-times the power of an automotive fuel cell. It is assumed that the larger scale of aircraft fuel cells will result in better performance metrics. The high values represent ambitious targets which would require technological breakthroughs to achieve.

Table 1. Range of system-level fuel cell parameters used in the analysis

Property	Low	Central	High
Fuel cell Specific power (kW/kg)	1.0	1.5	2.0
Fuel cell power density (kW/L)	0.75	1.0	1.25
Average fuel cell efficiency	0.45	0.55	0.65
Lifetime (hours)		8,000	
Fuel cell system cost ($/kW)		107	
Fuel cell system manufacturing emissions (kg CO_2e/kW)		50	

Fuel cells would likely need to be replaced several times within the lifetime of a retrofit aircraft. Current automotive fuel cells are designed to last for 5,000 hours of operation. The aspirational target, set by the U.S. Department of Energy (DOE), for the lifetime of a fuel cell is 8,000 hours (Padgett & Kleen, 2020). As a reference, a 700-km-long flight on a turboprop aircraft takes about 90 minutes. If an aircraft makes four daily flights (two round trips), its fuel cell would have to be changed in about 3.5 years. An aircraft's typical lifespan is 25–30 years, which would necessitate 7–9 fuel cell replacements during its lifetime. To account for replacements, this study includes the life cycle GHG emissions of producing a fuel cell in the operational carbon intensity of the fuel cell retrofit. This study also includes the cost of fuel cell replacement in the fueling cost of a retrofit aircraft.

The U.S. DOE aims to reduce the cost for an 80kW fuel cell system at an annual production volume of 100,000 systems to $30/kW (Padgett & Kleen, 2020); 80 kW is nearly 50 times smaller than the combined 3950 kW fuel cell system required to power an ATR 72 retrofit. Additionally, it is unlikely that a production volume of 100,000 systems per year will be reached before fuel cell aircraft enter the market. It is more likely that ~20 aircraft are retrofitted in a year, needing the equivalent of 1,000 80-kW systems. Wilson et al. (2017) estimate that fuel cell systems that cost $50/kW at 100,000 units per year would cost $179/kW at the lower production quantity of 1,000 units per year. Accordingly, fuel cell systems that cost $30/kW at 100,000 units per year would cost $107/kW at 1,000 units per year. This puts the unit cost for an aircraft fuel cell system at around $420,000.

This study uses a carbon intensity of 50 kg CO_2e/kW of output power for a fuel cell stack. This is based on a literature review that yielded GHG intensity values from 25–70 kg CO_2e/kW (Ballard Power Systems Inc., 2023; Dhanushkodi et al., 2008; Simons & Bauer, 2015; Usai et al., 2021).

ELECTRIC MOTORS

The electrification of passenger cars has spurred the development of high-performance motors built for transport. The motor of a Tesla Model S Plaid has a specific power of 8 kW/kg (Ingineerix, 2021; *Model S*, 2023). A leading electric propulsion manufacturer, magniX, previously listed a system-level specific power of 3.2 kW/kg for their magni650 electric propulsion unit (EPU) (magniX, 2022). The quoted weight includes the weight of the power electronics and the thermal management system, which explains the lower specific power compared to that of the Tesla motor. A fuel cell turboprop aircraft would require electric motors rated for ~2 MW, which is higher than these motors. For power density, this analysis referred to the specifications sheets of commercially available motors. Portescap, which specializes in compact motors, produces the 35ECS80 Ultra EC motor with a power density of 4.2 kW/L and a specific power of 0.75 kW/kg (Portescap, 2021).

Achieving the power output required to power an aircraft will not be a challenge; fitting a motor on an aircraft sensitive to added mass and volume will be. To test the sensitivity of aircraft performance to these key parameters, this study explores the ranges of values shown in Table 2. These values are for the EPU which includes the weight and volume for associated thermal management systems and power electronics in addition to the motor itself.

Table 2. Range of electric propulsion unit (EPU) parameters

Property	Low	Central	High
EPU specific power (kW/kg)	3.0	4.0	5.0
EPU power density (kW/L)	3.0	4.0	5.0

REFERENCE AIRCRAFT

The ATR 72 is the reference aircraft for this study. Appendix A details the reference aircraft selection process. Table 3 lists some of the technical characteristics and 2019 usage statistics of the ATR 72 (Graver et al., 2020). The ATR 72 was responsible for 39% of all turboprop ASKs and 40% of all turboprop departures. While the aircraft can carry 78 passengers 1370 km, its most common seating capacity in 2019 was 70; 90% of its routes were less than 700 km.

Table 3. Technical characteristics and 2019 usage statistics of the ATR 72

	ATR 72
Maximum passenger capacity	78
Most common passenger capacity	70
Range at maximum payload	1,370 km
Maximum takeoff mass	23,000 kg
Engine takeoff power (per engine)	1,846 kW
Median route distance	364 km
90^{th} percentile of route distance	700 km
ASKs in 2019	33 billion
Departures in 2019	1.5 million
CO_2 emissions in 2019	3.2 Mt

The fuel cell retrofitting process would necessarily reduce an aircraft's passenger capacity as hydrogen must be stored in the fuselage. To provide a comparison to an aircraft with a smaller passenger capacity, the results of this study include the performance of the Dash 8 Q300 which, according to this study's modeling, can carry 56 passengers 1,650 km.

This analysis also includes the performance of an LH_2 combustion turboprop aircraft that was modeled in a previous study (Mukhopadhaya & Rutherford, 2022). LH_2 combustion aircraft performance numbers in this study differ from the previous analysis due to a smaller reserve requirement (5 minute loiter time as opposed to a 45 minute loiter time in the previous work) inspired by changes being considered by the European Union Aviation Safety Agency (EASA) (EASA, 2022a). This study also models the aircraft to be carrying 78 passengers as opposed to 70 passengers modeled in the previous work.

AIRCRAFT RETROFITTING

Geometry

Retrofitting an aircraft would require minimal changes to its external geometry. The only external change would be replacing the Jet A powered turboprop engines with fuel cells that power electric motors. Modeling the size of the nacelle is important as it impacts the drag experienced by the aircraft.

The turboprop engine that powers an ATR 72, the Pratt & Whitney Canada PW127XT-M, has a diameter of 0.72 m and a length of 2.13 m resulting in a volume of 0.87 m^3. It is rated for a takeoff thrust of 1846 kW (EASA, 2022b). To fit a fuel cell propulsion system within the same nacelle as the turboprop engine, the electric motor and fuel cell system would need to have a combined power density of 2 kilowatts per liter (kW/L). Our baseline case sets the power density of a fuel cell at 1.0 kW/L, and of a motor at 4.0 kW/L.

The nacelle would need to be larger than the propulsion system itself. Modeling the nacelle of a retrofitted aircraft requires first calculating the combined volume of the fuel cell and electric motor based on the aircraft's takeoff power requirement and the components' power densities. This study assumes a propulsion system with the same aspect ratio as the PW127XT-M. The aspect ratio and combined volume are used to calculate the diameter and length of the propulsion system. This diameter and length are multiplied by 1.7 and 1.6, respectively, to determine nacelle dimensions.[1]

Fuel cells would also require bigger air inlets to dissipate generated heat (Gates, 2023). These are modeled by further increasing the nacelle's diameter by 5%. Figure 2 compares original and retrofitted nacelle sizes, under the baseline assumptions for a fuel cell propulsion system.

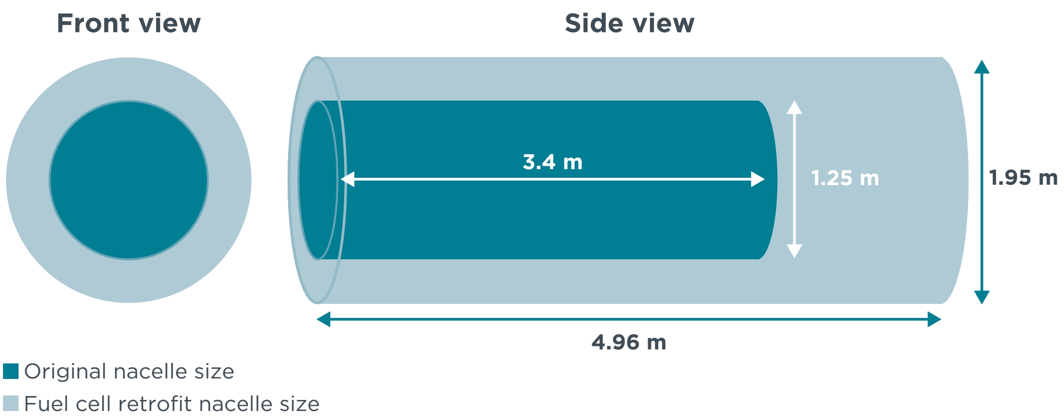

Figure 2. Comparison of the nacelle sizes.

Hydrogen Storage

Hydrogen must be compressed or liquified to increase its energy density. Liquifying hydrogen results in the highest energy density, but it still occupies four-times the volume of Jet A to provide the same amount of energy. Table 4 lists the relevant thermodynamic properties of Jet A, GH_2 stored at 700 bar, and LH_2 stored at -253° C (20 K).

1 The ATR 72's nacelle is 1.7 times wider and 1.6 times longer than the engine it houses.

Table 4. Thermodynamic properties of Jet A, GH_2 and LH_2

	Jet A	GH_2 at 700 bar	LH_2 at -253° C
Specific energy (MJ/kg)	43	120[2] (~2.8x)	
Density (kg/m³)	808	42 (~0.05x)	71 (~0.09x)
Energy density (GJ/m³)	34.7	5 (~0.14x)	8.5 (~0.25x)
Liquefaction/compression energy (kWh/kg)	-	2.9-3.2	10.0-13.0

Regardless of the state of hydrogen, hydrogen storage on an aircraft is a challenge. Jet A is carried in fuel tanks built into an aircraft's wings. These tanks conform to the shape of the wing and are lightweight. Neither GH_2 nor LH_2 could be stored in such tanks. Hydrogen must be stored inside an aircraft's fuselage. Within the fuselage, volume is limited. An aircraft retrofit would necessitate that passenger seating be replaced with hydrogen storage. Figure 3 overlays hydrogen tanks on a 78-passenger seating layout for the ATR 72. By replacing seven rows of seats, 14 tanks (seven rows of two vertically stacked cylindrical tanks) can fit in the fuselage.

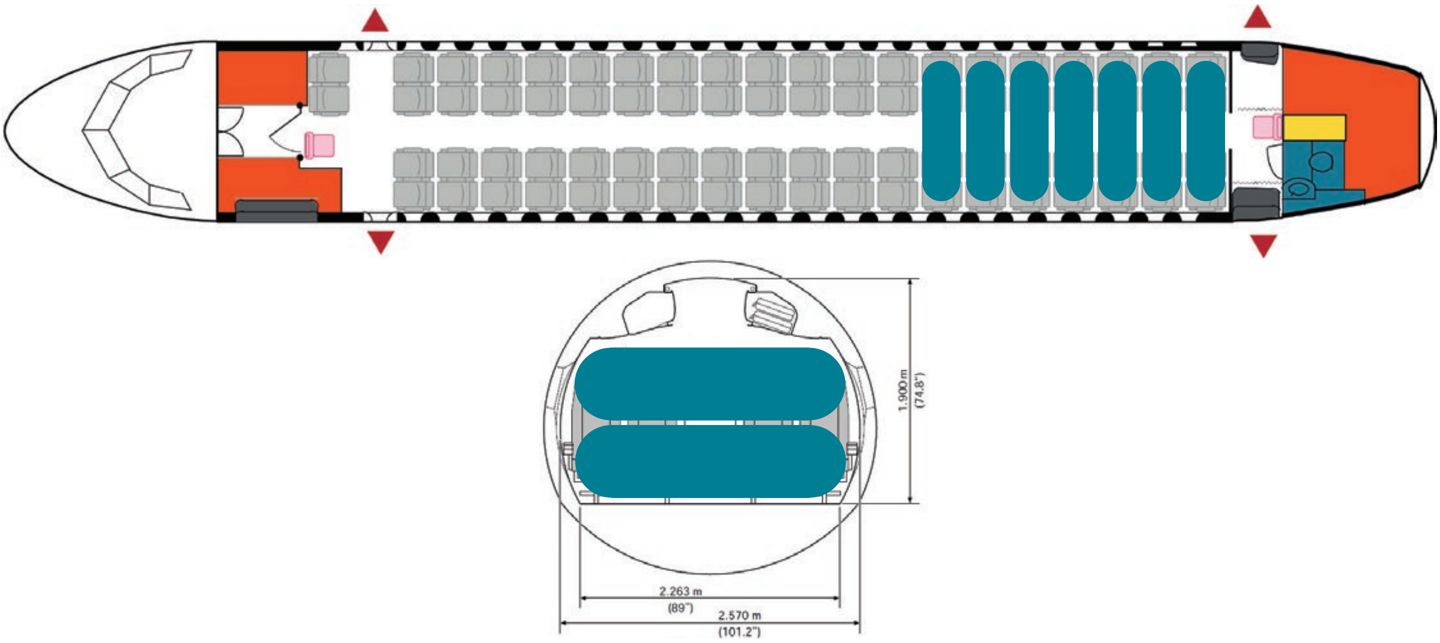

Figure 3. Illustrative tank layout of a retrofitted ATR 72 for 50 passengers.

This style of hydrogen storage is based on the solution that Universal Hydrogen has planned for their retrofitted aircraft. It relies on composite-construction hydrogen tanks, two of which would be stacked and held in place by a frame (Universal Hydrogen, 2023). Tanks would be sized such that the diameter of the tank is less than the distance between two rows of seats, and the length is such that it can fit in the cabin area of the aircraft. This distance between two rows of seats is known as the seat pitch. The 78-passenger configuration shown in Figure 3 has a seat pitch of 28 inches (0.71 m). This seat pitch is used for all analyses in this study. The dimensions of an individual tank are presented in Table 5. Tank wall thicknesses of 3.5 cm and 4.6 cm are used for the GH_2 and LH_2 tanks, respectively.[3] The same outer dimensions are used for both.

2 Not including fuel tank mass. The Lower Heating Value (LHV) of hydrogen is used here, as the product of hydrogen combustion is water vapor.

3 The 3.5 cm thickness for the GH_2 tank assumes composite material construction designed to withstand 700 bar pressurization with a factor of safety of 2.0. The 4.6 cm thickness for the LH_2 aircraft assumes a single wall construction with foam insulation and composite inner and outer walls (Verstraete, 2009).

Table 5. Hydrogen storage tank dimensions

Parameter	Value
Radius (m)	0.31
Length (m)	1.7
Wall thickness (m)	0.035 (GH_2), 0.046 (LH_2)
Internal volume (m^3)	0.47
GH_2 mass stored at 700 bar (kg)	20.6
LH_2 mass stored at 85% fill (kg)[4]	27.1

In addition to volume, the weight of the hydrogen storage is also a challenge. A kilogram of hydrogen provides nearly 3-times the energy as a kilogram Jet A. However, hydrogen storage tanks tend to be heavier than Jet A tanks. In addition to heavier fuel tanks, H_2-powered aircraft would require a modified fuel delivery system with redesigned fuel pipes, pumps, seals, and valves to handle the increased volumetric flow of hydrogen. As with the fuel cell, this study analyzes the system-level weight of hydrogen storage and delivery. For this purpose, this analysis defines the Gravimetric Index (GI) of the fuel system as:

$$GI = \frac{\textit{Mass of stored fuel}}{\textit{Mass of stored fuel} + \textit{Mass of the entire fuel system}} \tag{1}$$

where the fuel system refers to the empty weight of the storage tanks, any required heat exchangers, and all other ancillary fuel delivery components such as pipes, pumps, valves, and sealants.

The current state-of-the-art pressurized GH_2 storage (found in the Toyota Mirai) achieves a GI of 0.06 at 700 bar storage pressure. The GI is expected to increase with an increased use of composites in the tank structure; this study investigates GIs of 0.05–0.15 for the GH_2 fuel system. A tank pressure range of 300–900 bar is also investigated.

Structural and thermal analysis of LH_2 tanks suggests that a fuel tank GI of 0.5–0.8 (Gomez & Smith, 2019; Verstraete, 2009) can be achieved for tanks larger than those modeled here. This study investigates GIs in the range of 0.2–0.35 for the LH_2 fuel system. The hydrogen storage parameters used in this analysis are listed in Table 6.

Table 6. Range of hydrogen storage parameters used in the analysis

Property	Low	Central	High
GH_2 storage pressure (bar)	300	700	900
GH_2 storage gravimetric index	0.05	0.08	0.15
LH_2 storage gravimetric index	0.2	0.275	0.35

Hydrogen storage systems would have a limited lifespan as the cyclic nature of pressurization/cooling could cause material fatigue. For this analysis, a lifespan of 5,000 duty cycles is assumed along with a storage system cost of $300/kg of stored GH_2 and $400/kg of stored LH_2 (Houchins & James, 2022). This means each GH_2 tank would cost $6,180 while each LH_2 tank would cost $10,840. Similarly, life-cycle emissions of hydrogen storage systems are also included in the results. This study assumes 34.5 kg CO_2e /kg of GH_2 storage and 6.4 kg CO_2e/kg of LH_2 storage (derived from hydrogen storage systems for heavy duty vehicles) (Weiszflog & Abbas, 2022). The significantly higher emissions for GH_2 storage are a result of higher carbon fiber utilization, the main driver of life-cycle emissions values.

4 LH_2 tanks are not filled to greater than 85% to allow for some boil-off before the venting pressure of the tank is reached. This also accounts for the thermal contraction of the tank at cryogenic temperatures.

Weight estimation

This study uses weights provided by original equipment manufacturers to model the ATR 72 reference aircraft. The National Aeronautics and Space Administration's Flight Optimization System weight estimation method (Wells et al., 2017) is used to estimate the structural, avionics, and operating item weights of the fuel cell aircraft which would remain the same as the reference aircraft.

The weight of the new systems is estimated separately. Hydrogen storage system weights are specified according to the GI of the fuel system (Table 6). Fuel cell system and motor masses are calculated according to their specific powers (Table 1). Electrical system weights are calculated using Vahana's trade study on the design of electric vertical takeoff and landing aircraft (Bower, 2017; Vahana, 2016). For the payload weight estimation, this study assumes a passenger weight of 75 kg (165 lbs) and a baggage weight of 20 kg (44 lbs).

Sizing

In a retrofit of the ATR 72, wing and tail sizes would remain unchanged for all aircraft analyzed. However, while analyzing different passenger and hydrogen storage capacities, the aircraft's maximum takeoff mass (MTOM) can change. To ensure the aircraft could take off without significant change to takeoff field length, the maximum power output of the fuel cell and motor are sized linearly according to the MTOM. The weights of the components are scaled according to their specific power values. The sizing of the propulsion system is done within the weight estimation loop, so their effects are included in the final MTOM estimation.

Once the fuel cell power requirement for the heaviest variant of the retrofit is determined, the fuel cell power output is kept constant at that maximum value (1975 kW for this study) for all other variants. It is unlikely that different propulsion systems would be used for different variants.

Performance

The aircraft aerodynamic analysis and mission simulation is carried out using SUAVE, an open-source simulation environment built for conceptual vehicle design and optimization (Botero et al., 2016; Lukaczyk et al., 2015). A low-fidelity aerodynamic analysis is performed to rapidly calculate the lift and drag characteristics of the aircraft. This is known as the Fidelity Zero analysis (Lukaczyk et al., 2015).

SUAVE can model hydrogen fuel cell aircraft (Nicolay et al., 2021). The performance of a fuel cell system is defined by its system-level efficiency and specific power. A range of values for both these parameters investigated and the sensitivity of aircraft performance to these parameters is presented. The mission profile used to assess the energy intensity of hydrogen-powered designs is provided in Appendix B. Fuel reserves are included in all calculations.

Aircraft families

Aircraft manufacturers often create aircraft families, where the same wing is attached to fuselages of varying length to cater to airlines that might have different payload needs. For example, the ATR 72 has a smaller 48-seat variant in the ATR 42. This work analyzes aircraft of different passenger capacities by replacing rows of passengers with hydrogen storage (Figure 3). Removing one row of passenger seating (4-abreast) allows two vertically stacked tanks to fit into the fuselage.

Consequently, 7–8 seating configuration options are available, spanning a seating capacity of 42–70 passengers. All seating configurations have the same seat pitch of 28 inches (0.71 m). It may be possible for a retrofitting company to provide all those options for airlines looking to invest. It is more common for an aircraft model to have

2–3 variations with different length fuselages to accommodate different payload capacities. Instead of building different fuselages, retrofitting an aircraft with modular hydrogen storage could provide payload and fuel flexibility. For this study, we quantify the GHG mitigation that can be achieved in three scenarios: 1) Single: only one seating configuration is commercially available; 2) Family: three seating configurations are available, and 3) All: all possible seating configurations are available.

The maximum GHG mitigation was determined in each scenario for aircraft fueled by both GH_2 and LH_2. The Global Aviation Carbon Assessment (GACA) database is used to quantify the emissions from turboprop aircraft (Graver et al., 2020). Passenger travel on turboprops in 2019 emitted 9.1 Mt of CO_2e, or about 1% of total airline emissions. The GHG mitigation potential of fuel cell aircraft is calculated by comparing their emissions to those from fossil fueled aircraft. All missions that can be covered by a fuel cell aircraft in each scenario are considered. Fuel cell aircraft emissions are calculated by multiplying the amount of hydrogen used by the emission factors of GH_2 and LH_2. These values are then subtracted from the emissions of using fossil fueled aircraft on these missions to calculate the GHG mitigation potential.

For the Single and Family scenarios, this study analyzed subsets of possible seating configurations. For the Single scenario, this analysis chooses the one configuration that provides the highest GHG mitigation potential. For the Family scenario, this analysis chooses a combination of three configurations that provides the highest GHG mitigation potential.

REFERENCE MISSION SIMULATIONS

Fuel cell retrofit aircraft performance is compared to the reference aircraft on a variety of missions. The maximum range of fuel cell aircraft at each possible passenger seating capacity, from 42–70, is determined from the available fuel that would be held in the retrofitted fuselage tanks. The range and energy intensity are compared to those of the ATR 72 and the Dash8 Q300.

Next, these aircraft are compared on missions of 400 km and 700 km which are representative of real-world usage (based on turboprop routes flown in 2019). That year, the median route distance for an ATR 72 was 364 km; 90% of all missions flown by ATR 72s were less than 700 km.

FUEL ANALYSIS

This study compares the cost and carbon intensity of using green LH_2 and GH_2 in a fuel cell aircraft to the cost and carbon intensity of combusting Jet A, synthetic e-kerosene, and green LH_2 in a turboprop-powered aircraft.

Jet A is the fossil fuel used to power commercial air travel. E-kerosene is a synthetic jet fuel that can be used in existing aircraft engines as a drop-in replacement for Jet A. If produced using additional renewable electricity, green hydrogen, and carbon captured either as a waste from a point source or using direct air capture (DAC), e-kerosene can have lower carbon emissions than Jet A on a lifecycle basis. Green hydrogen is hydrogen produced using 100% additional renewable energy to power the electrolysis of water and the processing required to prepare it for use in transportation.

Both e-kerosene and green hydrogen need to be produced using additional renewable energy to minimize their GHG emissions. Renewable means the process of generating electricity emits no carbon (for example, when solar or wind are the energy source). Additionality requires that the electricity come from new renewable energy generation capacity, above and beyond existing plans for grid decarbonization. This ensures the energy used to produce these fuels is not diverted from existing uses.[5]

Carbon intensity

Carbon intensity calculations use the 100-year global warming potentials of methane (CH_4) and nitrous oxide (N_2O) to convert them into CO_2-equivalent (CO_2e) units (Intergovernmental Panel on Climate Change, 2013). This study does not estimate the warming impact of short-lived climate pollutants like NO_x, black carbon, water vapor, or contrail/cirrus. It does consider the lifecycle impacts of the fuels, including emissions associated with the creation of new renewable energy facilities to power the production of the alternative fuels.

To account for the carbon intensity of building renewable energy capacity, this analysis uses the Intergovernmental Panel on Climate Change's global average lifecycle GHG emissions of wind and solar photovoltaic electricity generation technologies (Moomaw et al., 2011). This study assumes the renewable energy is sourced from a 50-50 mix of photovoltaic solar and wind energy which results in a carbon intensity of 29 gCO_2e/kWh (Bieker, 2021). This value includes emissions associated with the construction and installation of energy production facilities, namely wind turbines and photovoltaic cells.

This carbon intensity of renewable electricity, and the energy conversion efficiency of producing each fuel, is used to calculate the carbon intensity of GH_2, LH_2, and e-kerosene. A 70% efficiency in producing hydrogen and a 6kWh/kg energy requirement to compress hydrogen to 700 bar results in an energy conversion efficiency of 62% (Christensen, 2020). Liquefaction takes 12 kWh/kg which results in an LH_2 energy conversion efficiency of 56%. Gaseous hydrogen is an input for e-kerosene production as well, however, additional energy is required to capture the carbon and for the Fischer-Tropsch synthesis process (Zhou et al., 2022). The overall energy efficiency of e-kerosene production can range from 46% (when carbon is captured using DAC) to 51% (when a point source is used to source the carbon). DAC is more expensive, less commercially developed, and less energy efficient. Consequently, this study assumes a point source for the carbon and uses 51% as the energy efficiency.

The carbon intensity of renewable energy is divided by the energy conversion efficiencies of various fuels to calculate each fuel's carbon intensity (Figure 4). The carbon intensities of the synthetic fuels are higher than in previous work (Mukhopadhaya & Rutherford, 2022), because this study includes the emissions associated with manufacturing and installing new renewable energy capacity. The Carbon Offsetting and Reduction Scheme for International Aviation's (CORSIA) carbon intensity value of 89 gCO_2e/MJ for Jet A is used for this work. Once aircraft performance is quantified, the gCO_2e/MJ value is multiplied by the energy intensity of the aircraft (measured in MJ/ASK) to account for the differing energy efficiencies of propulsion systems and to normalize the carbon intensity by ASK.

5 Failing to enforce additionality through policy measures such as power purchase agreements, plus proof that producers receive no subsidies or other policy support, could incentivize construction of new natural gas power plants to meet increased energy demand (Malins, 2019; O'Malley, 2021).

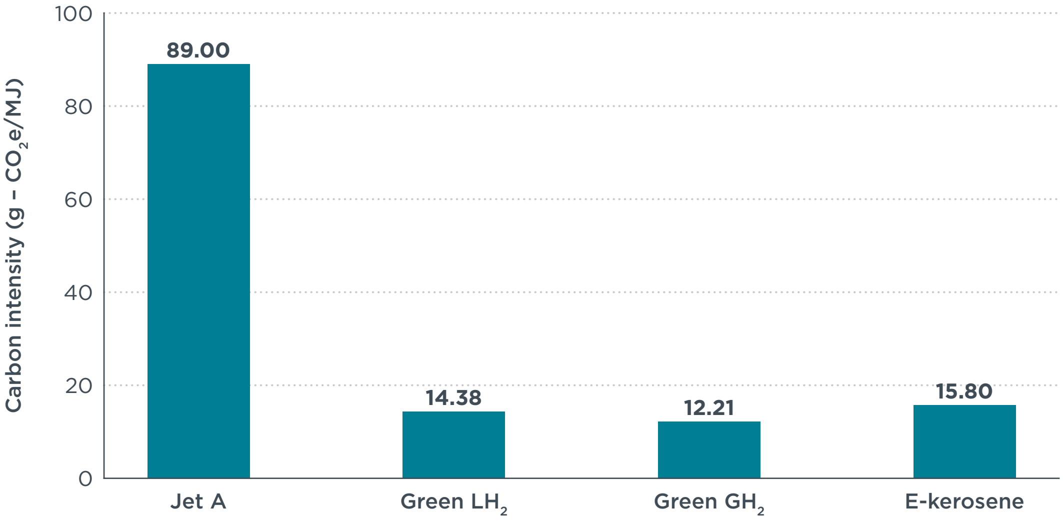

Figure 4. Fuel carbon intensities.

Cost

For the fuel price analysis, this study analyzes expected costs in 2030 and 2050 in the United States and the European Union (EU), two likely early markets for hydrogen fuel cell aircraft. Fuel cell powered aircraft are likely to be in commercial use by 2030; the International Civil Aviation Organization adopted a net-zero emissions goal for 2050 (Rutherford, 2022).

The cost of green hydrogen is broken into three components:

1. Cost of hydrogen production (Zhou et al., 2022).
2. Cost to liquify or compress the hydrogen (U.S. DOE, 2009).
3. Cost of the hydrogen refueling station (European Commission, 2021).

Appendix C details the cost estimation. Figures 5 and 6 present the pump price of green hydrogen and its breakdown by production, compression/liquefaction, and refueling. Green hydrogen is projected to be cheaper in the United States due to the lower cost of renewable energy. LH_2 is projected to be more expensive than GH_2 due to the higher energy requirement to liquify hydrogen and the higher cost of LH_2 refueling stations.

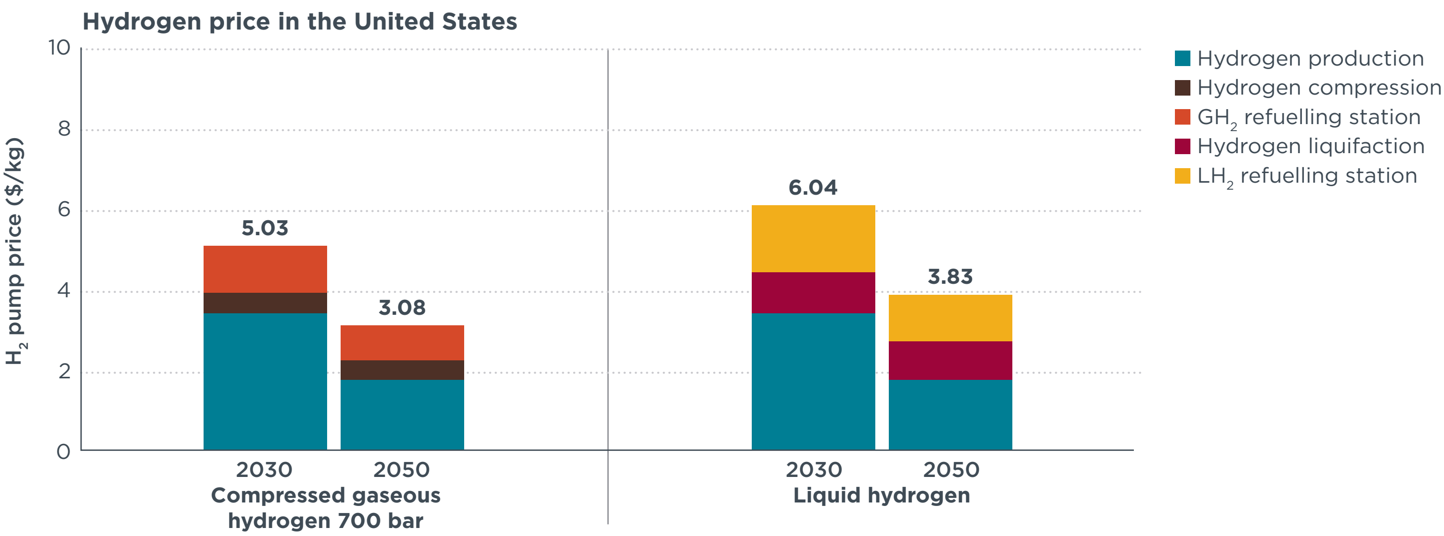

Figure 5. Pump price of hydrogen in the United States in 2022 USD.

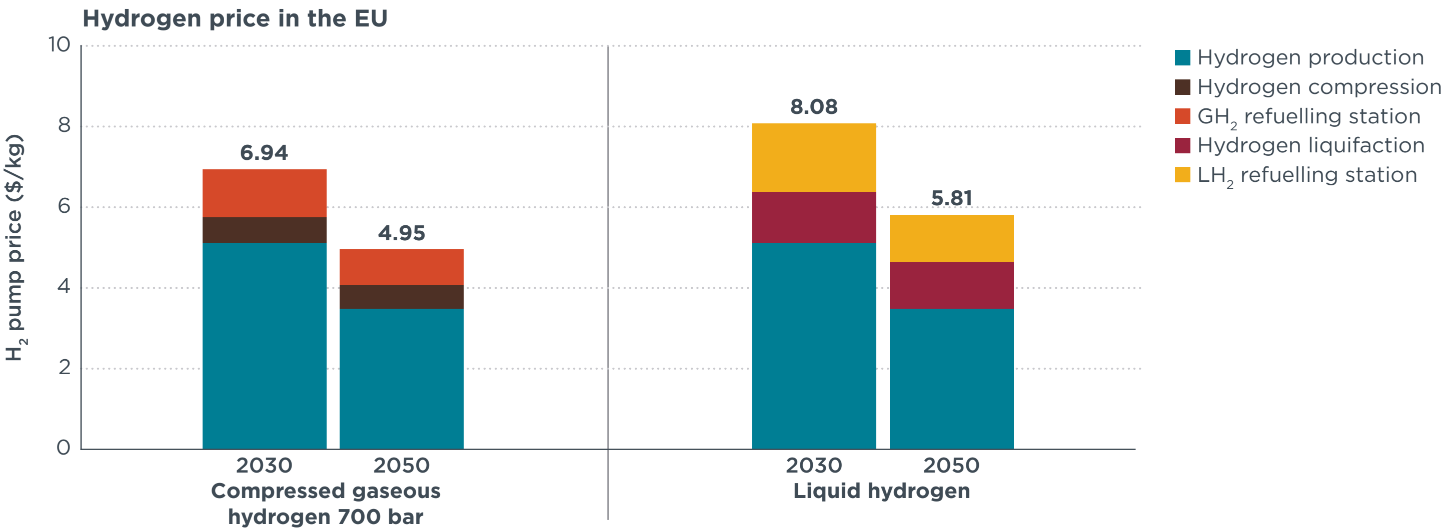

Figure 6. Pump price of hydrogen in the European Union in 2022 USD.

The cost of hydrogen is compared to the cost of Jet A and e-kerosene. Projecting fossil fuel prices is difficult due to market volatility. The price of Jet A in December 2022 from the International Air Transport Association's (IATA) 2023 Jet Fuel Price Monitor is higher than the projected price in 2030 and 2050 from the U.S. Energy Information Administration (U.S. EIA) reference-case projections (U.S. EIA, 2022). This analysis uses the December 2022 IATA price. The costs for e-kerosene are taken from previous ICCT work (Zhou et al., 2022). Since Jet A and e-kerosene have a specific energy and energy density different from hydrogen, costs must be normalized by energy instead of mass or volume.

Figure 7 compares the price of the different fuels considered in this analysis. In all cases, Jet A is cheapest, followed by green GH_2 and green LH_2, with e-kerosene the most expensive option. The prices of all alternative fuels are projected to decrease over the 2030–2050 time frame. Once aircraft performance is quantified, the $/MJ value is multiplied by the energy intensity of the aircraft (measured in MJ/ASK) to account the differing energy efficiencies of the propulsion systems and to normalize the fuel costs by ASK.

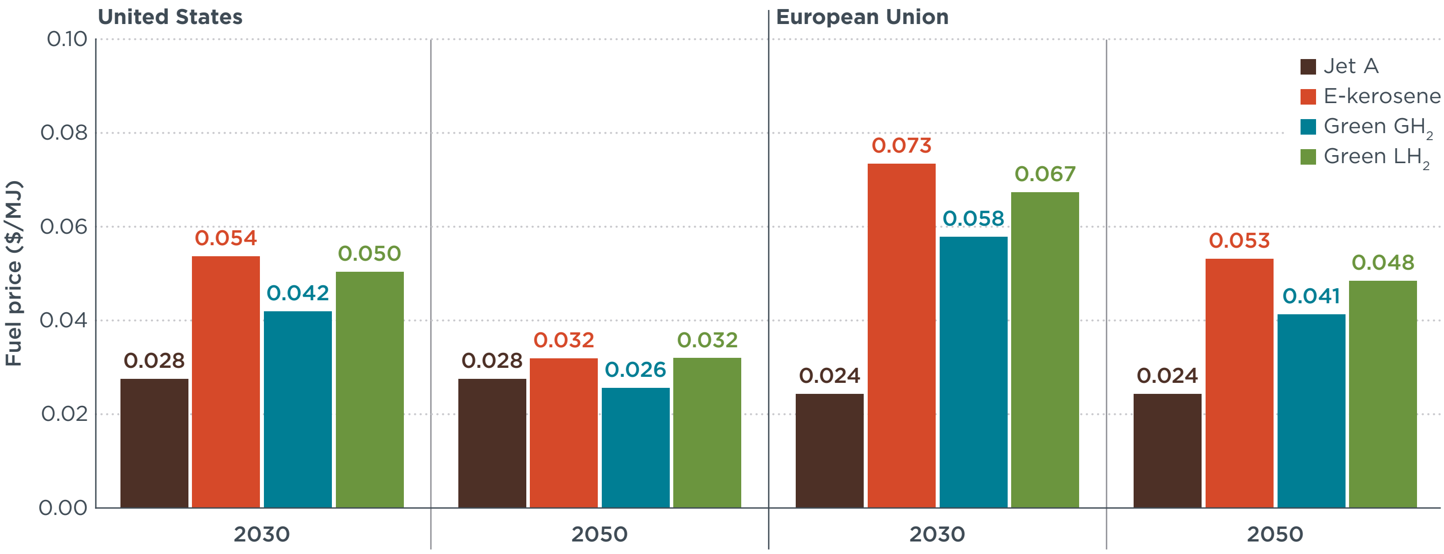

Figure 7. Fuel costs in 2022 USD by region and year.

RESULTS

This section presents this study's main results. All results except the sensitivity analysis were generated using the central values for the parameters introduced previously. First, this study determined the maximum range and transport efficiencies of carrying different amounts of hydrogen and passengers. The payload and range trade-off was compared to turboprop routes from 2019 to determine the optimum fuel load that maximizes the aircraft's GHG mitigation. A set of reference missions was used to compare the performance of the fuel cell retrofit aircraft to the reference fossil-fueled ATR 72 and an LH_2-combustion turboprop. The GHG emission intensity and cost of using GH_2 and LH_2 to power the fuel cell aircraft were then compared to those of using Jet A and e-kerosene to power the reference aircraft. Finally, this study assessed the sensitivity of the fuel cell retrofit aircraft to the various parameter assumptions.

RANGE COMPARISON

This work investigated a range of passenger capacities for the fuel cell retrofit, from 70 passengers to 42 passengers. This study simulated every possible configuration by removing one row of passengers at a time while adding two hydrogen tanks in that space. For example, a 70 passenger configuration fits four hydrogen tanks, whereas a 42 passenger configuration fits 18. Reducing an aircraft's passenger capacity increases its fuel carrying capacity and, consequently, its maximum range.

Figure 8 presents the maximum range and energy intensity at maximum range of the aircraft when all the available seats are full. For the fuel cell retrofit, results using both GH_2 and LH_2 are shown. Additionally, the performance of two Jet A fueled aircraft (an ATR 72 in its 78-seat configuration and a Dash 8 Q300 in its 56-seat configuration) are shown. Increasing the seating capacity of a fuel cell aircraft would reduce its maximum range due to increased payload weight and reduced hydrogen carrying capacity. Increasing passenger capacity would reduce an aircraft's energy intensity but with diminishing returns.

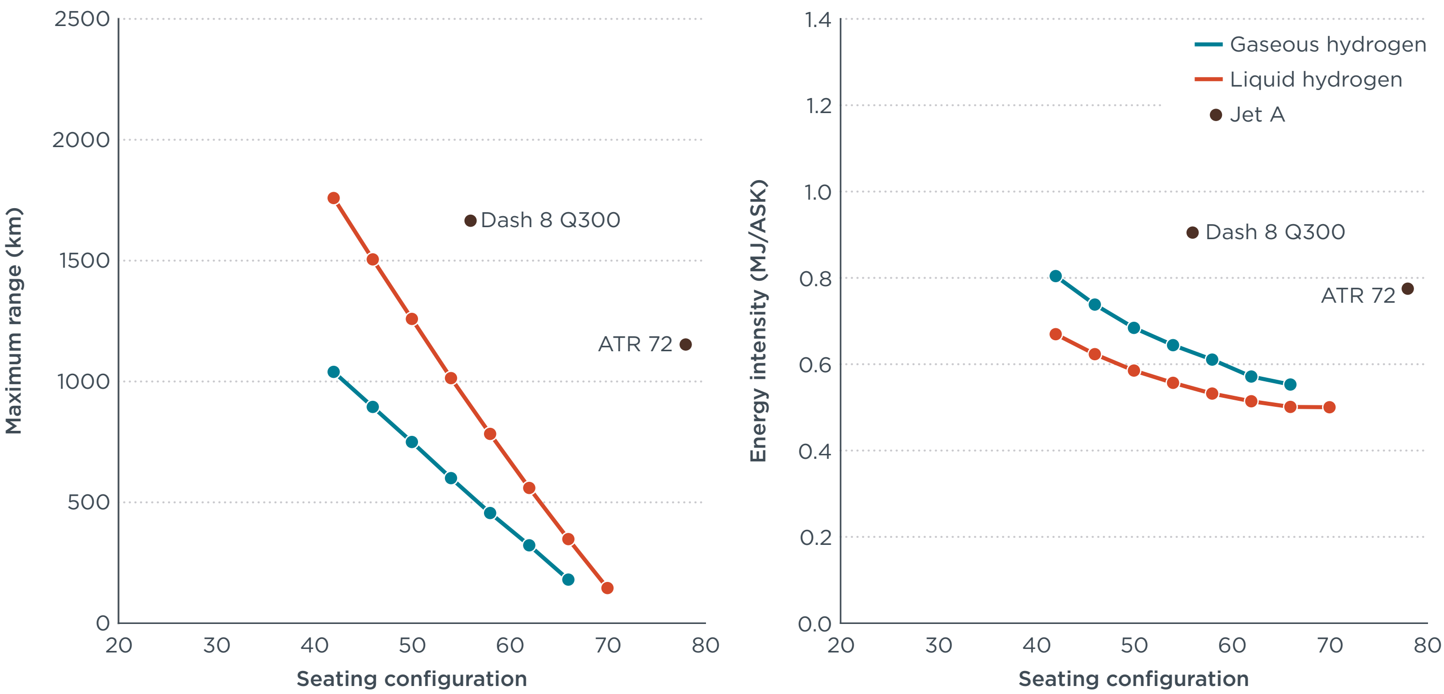

Figure 8. Maximum range (left) and energy intensity (right) of the fuel cell retrofit aircraft.

Comparing the use of GH_2 and LH_2, longer ranges are achieved by using LH_2 because the aircraft can carry more hydrogen for the same number of passengers. LH_2 tanks are also assumed to be lighter than GH_2 ones, which contributes to increased range. The longer range and lighter tanks also result in lower energy intensity when using LH_2.[6]

When compared to the fossil-fueled references, fuel cell aircraft are expected to have a lower payload capacity and shorter maximum range. This is primarily due to the volume that hydrogen and its tanks occupy. The impact of the hydrogen storage system on the MTOM would be minimal, with a maximum increase of 8% for the aircraft carrying GH_2. Most of the increased mass of a fuel storage system would be offset by the furnishings and passenger capacity that must be removed to fit hydrogen tanks.[7]

Fuel cell aircraft are expected to be more efficient than their fossil-fueled reference for a similar payload, but they could not travel as far. The Dash 8 Q300 carrying 56 passengers over 1,650 km requires 0.9 MJ/ASK. A fuel cell retrofit carrying 58 passengers can only travel about 456 or 783 km and requires 0.61 or 0.53 MJ/ASK when fueled by GH_2 or LH_2 respectively. Comparing the energy intensity for the same distance yields similar results; fuel cell aircraft are more efficient but take a payload penalty. LH_2-powered fuel cell aircraft could match the range of a Dash 8 Q300 but could only carry 42 passengers at an energy intensity of 0.67 MJ/ASK. The ATR 72 can carry 78 passengers 1150 km at an energy intensity of 0.77 MJ/ASK. An LH_2-fueled aircraft can match that range while carrying 54 passengers at a lower energy intensity of 0.56 MJ/ASK.

Fuel cell aircraft would be less energy intensive because fuel cells paired with electric motors convert energy more efficiently than turboprop engines. Turboprop engines usually have motor thermodynamic efficiencies in the range of 25-35% (National Academies of Sciences, Engineering, and Medicine, 2016) while a fuel cell aircraft could achieve energy conversion efficiencies of 44%.[8]

PAYLOAD AND FUEL STORAGE OPTIMIZATION

As explained in the aircraft families section, the Single and Family scenarios require choosing the optimal seating configurations that maximize the GHG mitigation impact of the aircraft. For the last scenario, All, this study assumes all seating configurations are available and quantifies their mitigation impacts.

For each scenario, the payload-range capability of the aircraft is compared to routes that were flown in 2019 to find the number of turboprop routes that could be serviced by such aircraft.[9] For brevity, only the payload-range diagrams for the Family scenario are shown in Figure 9. The left and right plots show the compressed GH_2 and the LH_2 cases, respectively. Each individual dot on the plot represents a turboprop route. The x-axis represents the range, and the y-axis represents the payload, expressed in seats available on the aircraft. The payload-range capabilities of the various aircraft are expressed by the solid lines. For the 50-seat variant fueled by GH_2 (Figure 9, left, blue line), the horizontal part represents the range when all 50 seats are filled. The range

6 When flying longer distances, an aircraft spends more time in its energy efficient cruise segment. This reduces a flight's overall energy intensity.

7 Each passenger is assumed to weigh 75 kg, their baggage is assumed to weigh 20 kg, and each seat is assumed to weigh 20 kg. Thus, one row of filled seats would weigh 460 kg. A set of two GH_2 tanks (GI = 0.08) that replaces the row of seats weighs 493 kg. Lower passenger capacity would also mean fewer service items and cabin crew. This would result in the MTOM varying by less than 1% across different passenger variants for a GH_2 powered aircraft.

8 This assumes a fuel cell efficiency of 55% and an electric efficiency of 80%. Since both engines use propellers, the propulsive efficiency is assumed to be the same for both aircraft.

9 This study compares to the aviation activity in 2019 as that was the last year without impacts from the coronavirus pandemic. The scope of this analysis was limited to only turboprop routes because turboprop aircraft are unlikely to replace turbofan aircraft which can fly at a faster cruise speed, covering the same mission ~1.5 times faster than a turboprop aircraft.

at this payload is 750 km (the corner point). If not all seats are filled, range increases slightly. This is represented by the line with the steep downward slope.[10] Routes plotted under and to the left of the aircraft's payload-range line can be serviced by that aircraft (shown as green dots). Routes that cannot be flown using these aircraft are shown as red dots.

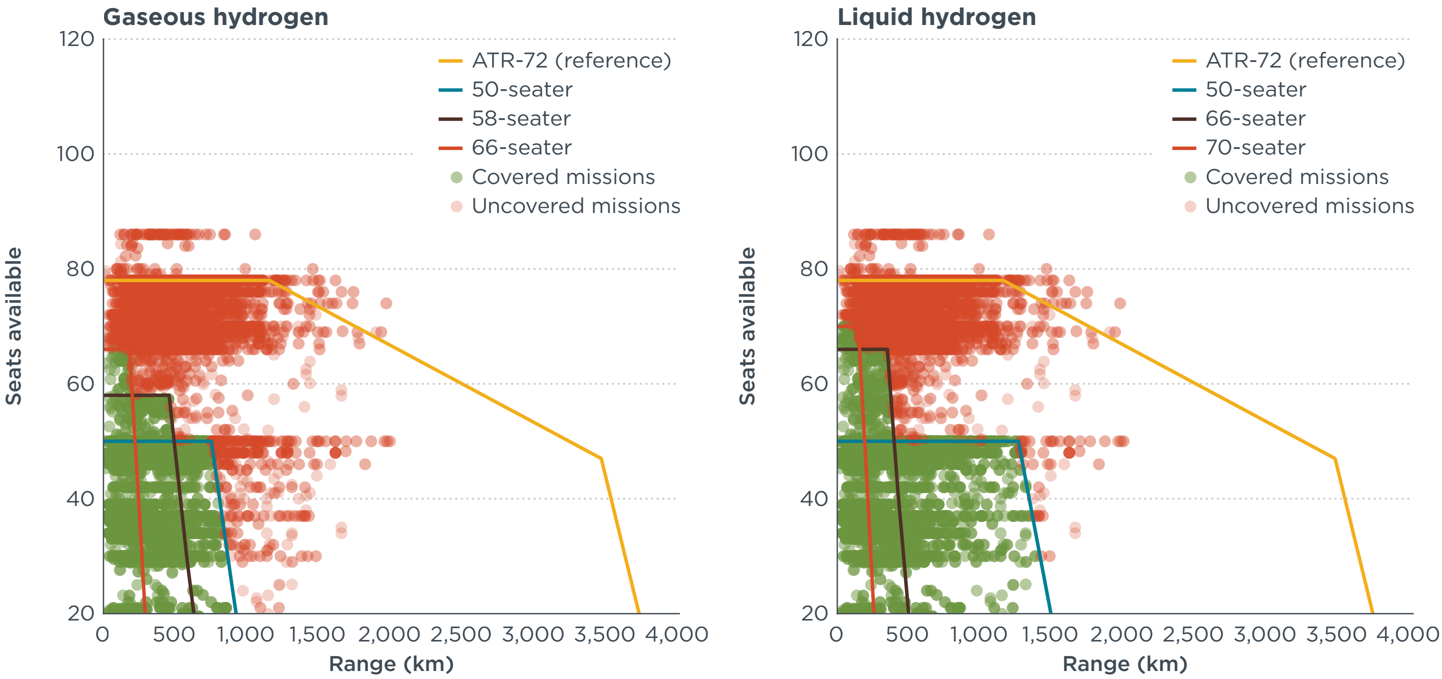

Figure 9. Turboprop routes flown in 2019 compared to the payload-range capability of fuel cell aircraft retrofits.

For the GH_2 case, the 50-seat configuration is the most effective configuration for the Single scenario and a combination of the 50-, 58-, and 66-seat configurations is the most effective for the Family scenario. For the LH_2 case, the 58-seat configuration is the single most effective, whereas the 50-, 66-, and 70-seat configurations are the most effective family. The use of more energy dense LH_2 would enable fewer fuel tanks and, therefore, more passengers compared to GH_2.

Table 7 presents the share of turboprop ASKs and departures that could be covered by fuel cell aircraft under each scenario and for both forms of hydrogen. The Family scenario provides more significant improvements in the LH_2 case due to the inclusion of the high passenger capacity variants. In the GH_2 case, those variants do not have enough range to provide substantial GHG mitigation potential. In both cases, the All scenario does not provide a significant improvement over the Family scenario.

10 The payload-range diagram of the ATR 72 has an additional corner which is absent from those of the H_2-powered aircraft. Fossil-fueled aircraft at their MTOM and maximum payload capacity (first corner) are often not at their maximum fuel capacity. When the payload is reduced, more fuel can be added to keep the aircraft at its MTOM, thus increasing the range sharply. This continues until the aircraft reaches its maximum fuel capacity (second corner). Beyond this, no additional fuel can be added, and the payload-range diagram falls rapidly as the payload is reduced without adding fuel to increase range. In contrast, the H_2-powered aircraft at their MTOM are at maximum payload and maximum fuel capacity (first and only corner). When the payload capacity is reduced, fuel cannot be added to keep the aircraft at MTOM. Consequently, the payload-range diagram starts falling rapidly.

Table 7. Turboprop route coverage for each fuel cell aircraft scenario

Fuel	GH_2			LH_2		
Scenario	**Single**	**Family**	**All**	**Single**	**Family**	**All**
Number of seats	50	50, 58, 66	42–66	58	50, 66, 70	42–70
Turboprop ASK coverage	15%	16%	17%	16%	19%	20%
Turboprop departure coverage	29%	31%	31%	31%	36%	36%

For all scenarios, the payload penalty for carrying tanks of hydrogen instead of passengers limits the ASK that can be covered by the aircraft. For example, in the Single scenario, both the 50-passenger GH_2 fueled aircraft and the 58-passenger LH_2 fueled aircraft can fly longer than 85% of all turboprop routes. As they cannot directly replace aircraft that carry 60 or more passengers, the ASK coverage remains at 15–16%. If, however, the addressable market was calculated purely based on range and if higher passenger capacity flights could be replaced with more frequent, smaller passenger capacity flights, then the ASK coverage for the Single scenario would increase to 85% and 88% for GH_2 and LH_2 respectively.

REFERENCE MISSION SIMULATIONS

Having determined the ideal payload and hydrogen storage combination for fuel cell aircraft, their performance can be directly compared to the ATR 72. This study used the best configurations for the GH_2 and LH_2 fueled aircraft (the 50-seat and 58-seat variants, respectively). Here, the performance of an LH_2 combustion turboprop aircraft that was modeled in previous work was included (Mukhopadhaya & Rutherford, 2022).

Maximum range missions

When comparing the performance of these aircraft at their maximum range, it is important to note that this study compares across different distances and different passenger capacities. Table 8 presents the results of the maximum range simulations of the different aircraft. As described earlier, fuel cell retrofits would have similar MTOM and lower payload and range capabilities, but would be more energy efficient than the ATR 72.

Table 8. Weights, range, and energy intensities of the turboprop aircraft

	ATR 72	Fuel cell retrofit		LH_2 combustion turboprop
		GH_2	LH_2	
Passengers	78	50 (-36%)	58 (-26%)	78
MTOM (kg)	23,000	24,700 (+8%)	22,900 (-0.03%)	25,600 (+11%)
Range (km)	1,150	750 (-38%)	783 (-15%)	845 (-27%)
Energy intensity (MJ/ASK)	0.77	0.68 (-12%)	0.53 (-31%)	0.87 (+13%)

While fuel cell propulsion could enjoy an energy conversion efficiency nearly 50% higher than that of turboprop engines, the difference in energy intensity, measured in the amount of energy required per ASK, would be more modest at a 12%–31% reduction. This is due to the lower passenger capacity and the shorter range of the fuel cell aircraft. Both factors reduce the number of ASKs achieved by the aircraft in a maximum range mission, thus increasing the energy required per ASK.

Representative missions

Aircraft are usually used on missions that are shorter than their maximum range. The ATR 72 has a maximum range of 1,370 km but its median route length in 2019 was 364 km; 90% of its routes were 700 km or less. This study simulated aircraft performance on routes of 400 km and 700 km. These distances are more representative of real-world usage of the aircraft. Table 9 presents the energy and emission intensities of the different aircraft on these missions. There are no significant differences between performances on two routes.

There would be an energy intensity advantage of the fuel cell retrofit over the original ATR 72. The carbon intensity of the fuel cell turboprop would be significantly lower (nearly a 90% reduction, owing to the low carbon intensity of green GH_2 and LH_2). The lower energy intensity of fuel cell propulsion would help narrow the price gap between Jet A and green hydrogen, bringing the price premium to 29%-40% in the United States in 2030.

The LH_2 combustion turboprop could match the passenger capacity of the ATR 72 but would suffer from the highest energy intensity of the aircraft considered. This is due to both the lower energy conversion efficiency of hydrogen combustion compared to a fuel cell and the increased MTOM of the LH_2 combustion turboprop aircraft. This would penalize the aircraft with a higher carbon intensity and fuel cost compared to a fuel cell aircraft.

Table 9. Energy and emissions intensity of turboprop aircraft

Mission	Parameter	ATR 72	Fuel cell turboprop		LH_2 combustion turboprop
			GH_2	LH_2	
Median mission 400 km	**Passengers**	78	50 (-36%)	58 (-26%)	78
	Fuel burn (kg)	617	118 (-80%)	104 (-83%)	250 (-59%)
	Energy Intensity (MJ/ASK)	0.86	0.71 (-17%)	0.54 (-36%)	0.96 (+12%)
	Carbon intensity (g-CO_2e/ASK)	76.1	10.9 (-86%)	8.8 (-88%)	14.0 (-82%)
	$ fuel/ASK (2030, U.S.)	0.024	0.033 (+40%)	0.030 (+29%)	0.052 (+120%)
90% mission 700 km	**Passengers**	78	50 (-36%)	58 (-26%)	78
	Fuel burn (kg)	1,006	200 (-80%)	180 (-82%)	410 (-59%)
	Energy Intensity (MJ/ASK)	0.80	0.69 (-13%)	0.53 (-33%)	0.90 (+13%)
	Carbon intensity (g-CO_2e/ASK)	70.9	10.1 (-86%)	8.6 (-88%)	13.1 (-82%)
	$ fuel/APK (2030, U.S.)	0.022	0.032 (+44%)	0.029 (+34%)	0.047 (+116%)

GHG MITIGATION POTENTIAL

Because retrofitting is uncommon in the aviation industry, it is difficult to model the expected delivery rates and fleet adoption of a retrofit aircraft. Instead, it is possible to model the annual impact of retrofitting one ATR 72. This requires assuming a typical annual usage for the ATR 72 and comparing the GHG emissions of an original Jet A fueled aircraft to that of a fuel cell retrofit. Since a fuel cell retrofit and ATR 72 would have different passenger capacities, having the same number of flights for both aircraft would result in fewer ASKs flown by the fuel cell variant and would disadvantage the fossil-fueled ATR 72. Therefore, the usage must be compared on an ASK basis, rather than a departure basis.

The ATR 72 performing four daily 400 km flights (two round trips) for 300 days in a year with flights always full with 78 passengers (consistent with the reference case) would equate to 37.4 million annual ASKs. At a carbon intensity of 76.1 gCO_2e/ASK, the ATR 72 would emit 2,850 tonnes of CO_2e in a year of operations. To cover the same number of ASKs in a year, a fuel cell retrofit would emit only 325 to 362 tonnes of

CO_2e depending on whether it would be fueled by LH_2 or GH_2, respectively.[11] Therefore, retrofitting one ATR 72 with fuel cell propulsion would mitigate around 2,500 tonnes of GHG emissions annually.

FUELS ANALYSIS

The 400 km mission is used for the fuel analysis. The carbon intensity and fuel cost of using GH_2 and LH_2 to power a fuel cell retrofit aircraft were compared with those of using Jet A and e-kerosene to power an ATR 72. The scope of the GHG emission intensity includes the life-cycle emissions of the fuel and the fuel cell production. This study does not include emissions from aircraft manufacturing, maintenance, or end-of-life uses.

Figure 10 illustrates carbon intensities. Carbon intensity is normalized by ASK to account for different aircraft ranges and payload capacities. For fuel cell aircraft, this study includes the carbon intensity of producing the fuel cells and hydrogen storage (since they need replacement over an aircraft's lifetime). Fuel cell production emissions are about 15% of the total emission intensity of a fuel cell aircraft. Fueling an ATR 72 with e-kerosene would reduce carbon intensity by 82%. This is comparable to the 87–88% reduction for a fuel cell retrofit aircraft.

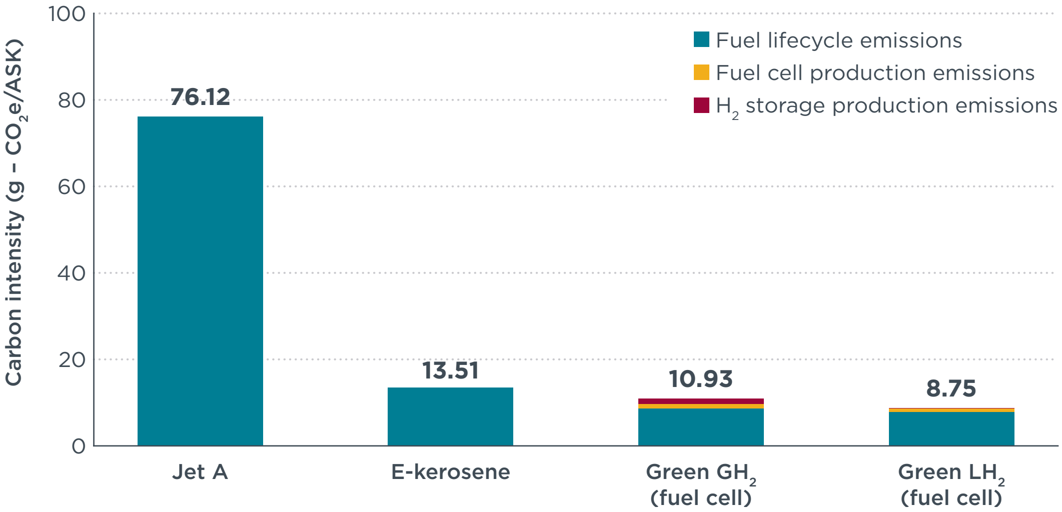

Figure 10. Carbon intensity of different fueling options.

To compare fueling costs, this study considered two regions, the United States and EU, and two years, 2030 and 2050. Since fuel cells and hydrogen storage must be replaced multiple times in an aircraft's lifetime, the cost of fuel cells and hydrogen storage are included in the cost analysis. The results are shown in Figure 11. The higher transport efficiency of using hydrogen fuel cell retrofits narrows the price gap with Jet A, making hydrogen a cheaper option in the United States in 2050. LH_2 would be cheaper than GH_2 on a per ASK basis as the higher efficiency of an LH_2 aircraft would compensate for the higher cost of producing the LH_2. E-kerosene would be the most expensive option (30–50% more expensive than hydrogen depending on year and region).

11 The fuel cell retrofit aircraft would need to fly, at minimum, one additional daily round trip (two flights) to offset lower passenger capacity.

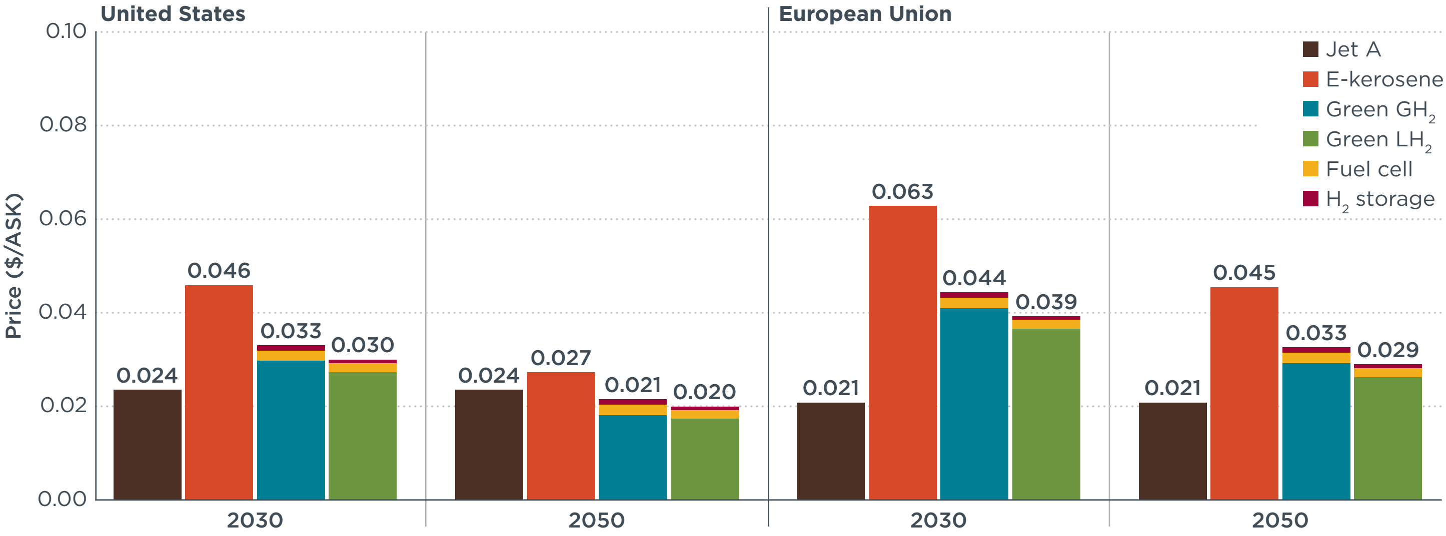

Figure 11. Fueling costs for turboprop aircraft by fuel, 2022 USD.

SENSITIVITY ANALYSIS

Modeling of a fuel cell retrofit required many assumptions and projections for parameters that impact aircraft performance. Performing a sensitivity analysis gives insight into the parameters that have the biggest impact. Figure 12 presents tornado charts for the aircraft range when using GH_2 while carrying 50 passengers (top) and LH_2 while carrying 58 passengers (bottom).

For both aircraft, fuel cell efficiency would most influence aircraft performance with an 18% change in the efficiency creating nearly a 25% change in range. For a GH_2 aircraft, storage pressure would significantly impact range given the change in the amount of hydrogen that can be carried. GH_2 storage at 300 bar (30 MPa), rather than 700 bar, would nearly halve an aircraft's range. 700 bar storage (or higher) would be required for GH_2-fueled aircraft to be viable. The gravimetric index of a fuel storage system would have a larger impact in the GH_2 case than the LH_2 case due to the lower GI values explored. Even though the range of values explored in the GH_2 case (0.05–0.1) is smaller than those explored in the LH_2 case (0.2–0.35), the impact on the range would be larger.

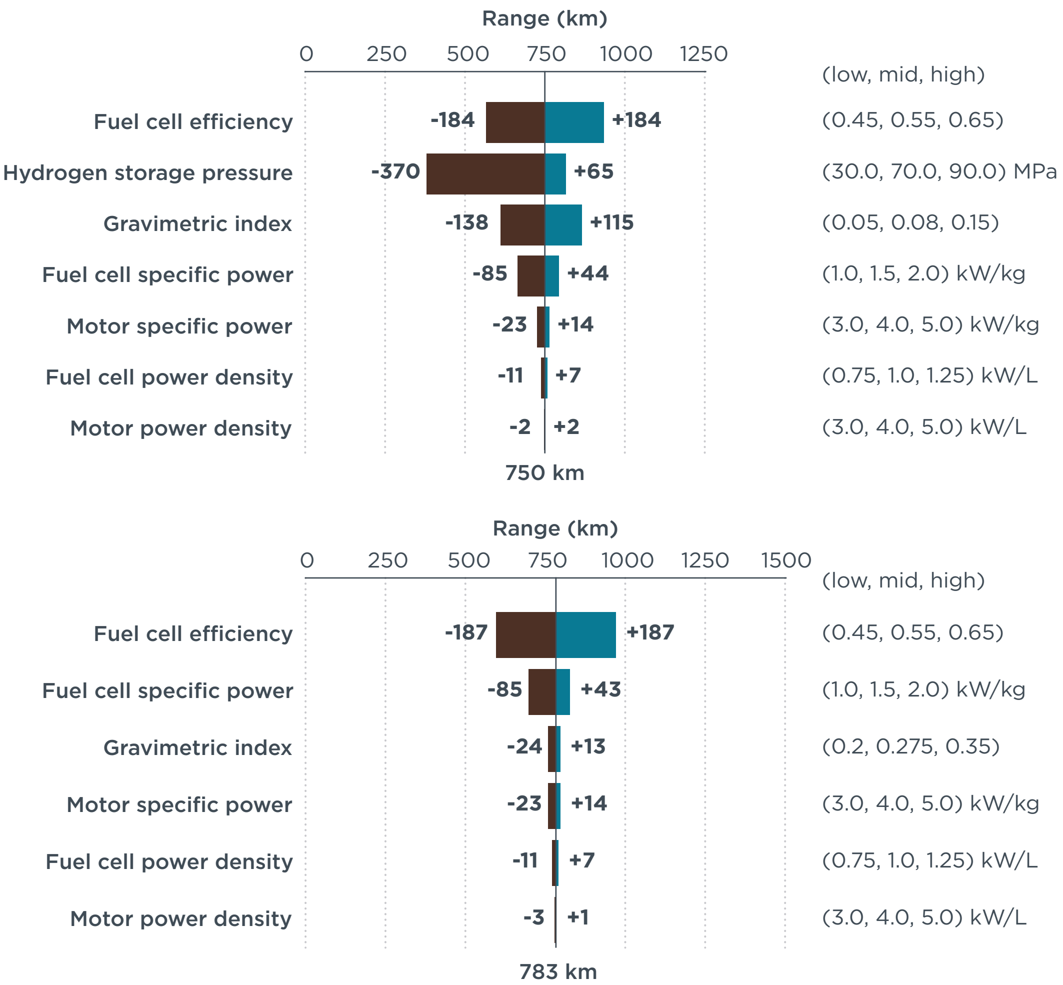

Figure 12. Sensitivity analysis of aircraft range. Top: GH_2 aircraft with 50 passengers. Bottom: LH_2 aircraft with 58 passengers.

Fuel-cell-specific power would moderately impact the performance of both aircraft. Motor parameters and the fuel cell power density minimally impact the range of both aircraft.

In addition to indicating which parameters could best predict aircraft performance, this sensitivity analysis can also help prioritize efforts to improve those parameters. Fuel cell efficiency gains would have an outsize impact on aircraft's range. There could be a benefit to using overpowered fuel cells that would allow an aircraft to operate at a lower throttle setting (the efficiency benefit of which could outweigh the penalty of a larger, heavier fuel cell system). In contrast, efforts to improve fuel cell or motor power density would have little impact on range.

CONCLUSIONS

This study analyzed the performance of a fossil-fueled regional aircraft retrofitted with a hydrogen fuel cell propulsion system. Its performance was compared to the original aircraft and hydrogen combustion aircraft. The carbon intensity and cost of fueling the aircraft with Jet A, e-kerosene, GH_2, and LH_2 were quantified. Finally, a sensitivity analysis to the modeling parameters was carried out. This analysis resulted in six key conclusions:

1. **Retrofitting an ATR 72 with hydrogen fuel cell propulsion would result in a more energy efficient aircraft.** Even though a retrofit aircraft would pay a penalty in payload and range, the higher efficiency of a fuel cell propulsion system would result in lower energy intensity per ASK.
2. **Using green hydrogen to power a retrofit fuel cell aircraft would result in nearly a 90% reduction in GHG emissions.** Even when accounting for the lifecycle emissions of renewable energy used to produce hydrogen, a retrofit aircraft operated on green hydrogen could produce 90% lower GHG emissions than a fossil fueled reference. If a fossil fueled reference were fueled by e-kerosene, a low carbon drop-in substitute for Jet A, the retrofit would still produce 30% lower GHG emissions in comparison.
3. **The increased efficiency of a fuel cell propulsion system would narrow the price premium of using green hydrogen.** While green hydrogen is expected to be more expensive than jet fuel in most cases, the increased efficiency of a fuel cell propulsion system would bring the price premium down to 29%–40% in the United States in 2030 and could make fueling with green hydrogen cheaper in the United States in 2050. In the EU, where hydrogen is expected to be more expensive to produce, the price premium would be around 100% in 2030, dropping to 50% in 2050.
4. **Fueling with LH_2 would increase the range of a fuel cell aircraft.** The higher density of LH_2 would increase the amount of hydrogen carried on an aircraft, increasing its range. Lighter tanks also make aircraft lighter, further reducing its energy intensity. This increased efficiency would offset the higher cost and carbon intensity of producing LH_2.
5. **Fuel cell retrofit aircraft could have the payload and range capability to service 15%–20% of the turboprop market.** Despite lower payload and range capabilities, retrofit aircraft could fly nearly one-fifth of all turboprop ASKs from 2019. This represents 29%–36% of all turboprop departures.
6. **Increasing the efficiency of a fuel cell would be the most effective way to improve aircraft performance.** A sensitivity analysis on the modeling parameters shows the importance of fuel cell efficiency to aircraft range. Factors such as the GH_2 storage pressure and the GI of the system are also important. Fuel cell and electric motor power density are less important as they reside outside the fuselage and would not impact the amount of hydrogen carried.

Areas for further research were highlighted in the course of this work. The narrowed scope of analyzing a retrofit aircraft brings up the question of the performance of clean-sheet designs of hydrogen aircraft. While several studies in this realm were highlighted in the introduction, most do not address the relevant market, do not perform a sensitivity analysis, and do not quantify the carbon intensity or cost of using green hydrogen. This work makes some progress in quantifying the infrastructure costs of hydrogen refueling stations, however further research into the infrastructure requirements at airports is required.

Retrofitting a fossil-fueled turboprop aircraft with hydrogen fuel cell propulsion could result in an aircraft that is more energy efficient and less carbon intensive, but more expensive to fuel. It would have lower payload and range capabilities than the original but could reduce GHG emissions by nearly 90% compared to the original aircraft.

POLICY RECOMMENDATIONS

As earlier market entrants, fuel cell retrofit aircraft could help develop hydrogen infrastructure at airports. They could provide an initial testbed that could be scaled to prepare for the introduction of larger, clean-sheet hydrogen combustion aircraft that could decarbonize a larger section of the aviation market. But dedicated policy support would be needed because their large-scale adoption is hampered by the state of fuel cell technology and the high price of green hydrogen.

Several policies are under development that could support these aircraft. The EU is currently considering ReFuelEU, a regulation that would instate blending mandates for drop-in sustainable aviation fuels that ramp up over the 2025–2050 timeframe. Long-term regulation with intermediary targets, such as ReFuelEU, provides a valuable policy signal to spur large-scale development of a nascent technology. Including green hydrogen and renewable electricity under the synthetic aviation fuels definition (Baldino & Mukhopadhaya, 2022) would give airlines flexibility in the aircraft propulsion systems they use to meet the mandates. It would also ensure a level playing field for technology and provide a long-term policy signal to spur development in hydrogen powered and electric aircraft.

Including green hydrogen and renewable electricity in ReFuelEU would also make them eligible for the use of 20 million free allowances set aside under the EU Emissions Trading System for the uplift of sustainable aviation fuels defined under ReFuelEU (Council of the European Union, 2022). The 2024–2030 timeframe makes this particularly applicable to fuel cell retrofit aircraft, which are likely to enter the commercial aviation market before 2030. The use of free allowances will alleviate some of the price premium of using green hydrogen as a fuel, making the retrofit of turboprop aircraft a more attractive option.

In the United States, California's Low Carbon Fuel Standard could be expanded to cover intra-state aviation. Amending the standard to include zero-emission aviation technologies, with appropriate energy efficiency ratios to reflect the higher efficiency of fuel cell and electric propulsion systems, could spur their development as it has done for electric and hydrogen powertrains in the road sector (Pavlenko & Mukhopadhaya, 2023).

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APPENDIX A: REFERENCE AIRCRAFT SELECTION

This analysis considers two of the most popular turboprop aircraft: the ATR 72 and the DeHavilland Canada Dash 8 Q400. They occupy the top two spots in turboprop departures and available seat kilometers. Table A1 lists some of their relevant specifications. The Dash 8 Q400 is a bigger aircraft with a larger passenger capacity and a higher MTOM. The engine power requirement is correspondingly higher as well (ESEA, 2014, 2022b).

Table A1. Relevant technical specifications of the ATR 72 and Dash 8 Q400

	ATR 72	Dash 8 Q400
Maximum passenger capacity	78	90 (+15%)
Range at maximum payload	1,370 km	2,040 km (+49%)
Maximum takeoff mass	23,000 kg	30,481 kg (+33%)
Engine takeoff power (per engine)	1,846 kW	3,781 kW (+105%)

While a bigger aircraft with a larger capacity would afford more hydrogen storage space, the higher power requirement for the Dash 8 Q400 is the reason this study uses the ATR 72 as the reference aircraft instead. Current commercially-available PEMFC stacks can produce up to 100 kW (U.S. DOE, Office of Energy Efficiency and Renewable Energy, 2021). Both aircraft would require either the development of higher power fuel cell stacks or the combining of multiple stacks to power the aircraft. However, the ATR 72 power requirement is less than half that of the Dash 8 Q400 with only a 12-passenger (15%) payload penalty. They are equally popular in commercial aviation (Graver et al., 2020).[12]

When comparing the real-world usage of these aircraft (Table A2), both aircraft are operated on routes that are significantly shorter than their stated ranges. 90% of ATR 72 routes are 700 km or shorter; 90% of Dash 8 Q400s routes are 1,000 km or shorter (Graver et al., 2020). While the Dash 8 Q400 is responsible for more ASKs and CO_2 emissions, the ATR 72 is responsible for more departures. Given the combination of the significantly lower power requirement and similar market coverage, the ATR 72 was chosen for this retrofit analysis.

Table A2. 2019 operations data for the ATR 72 and Dash 8 Q400

	ATR 72	Dash 8 Q400
Most common passenger capacity	70	78
Median route distance	364 km	513 km
90th percentile of route distance	700 km	1,000 km
ASKs in 2019	33 billion	37 billion (+12%)
Departures in 2019	1.5 million	1 million (-33%)
CO_2 emissions in 2019	3.2 Mt	3.8 Mt (+13%)

12 The ATR 72 was responsible for 39% of all turboprop ASKs in 2019 while the Dash 8 Q400 had a slightly larger share at 43%. However, in terms of departures, the ATR 72 represented 40% of all turboprop departures while the Dash 8 Q400 represented 29%.

APPENDIX B: AIRCRAFT MISSION PROFILE

Aircraft missions are defined by a sequence of climb, cruise, and descent segments. The Piano 5's default mission for the reference aircraft is a template. Accordingly, the turboprop mission segments are:

1. Climb to 1,500 feet at a constant Calibrated Airspeed (CAS) of 64 m/s and a climb rate of 1,650 ft/min.
2. Climb to 10,000 feet at a constant CAS of 75 m/s and a climb rate of 1,330 ft/min.
3. Climb to 20,000 feet at a constant CAS of 75 m/s and a climb rate of 1,000 ft/min.
4. Cruise at 20,000 feet at Mach 0.452.
5. Descent to 10,000 feet at a constant CAS of 100 m/s and a descent rate of 1,060 ft/min.
6. Descent to 1,500 feet at a constant CAS of 100 m/s and a descent rate of 1,020 m/s.
7. Descent to 35 feet at a constant speed of 55 m/s and a descent angle of 3°.

For simplicity and direct aircraft performance comparisons, step-up cruise segments are not used. The cruise segments for both aircraft are at a constant altitude and constant Mach number. However, for flights shorter than 350 km, the cruise altitude is set to 15,000 feet; for flights shorter than 250 km, the cruise altitude is set to 12,000 feet. It is inefficient for these flights to climb to higher altitudes as they spend extra energy climbing but do not spend enough time at the high altitude to reap the benefits of lower drag during the cruise segment.

The following fuel reserves are included when determining aircraft range:

1. Flight to an alternate airport 185 km (100 nautical miles) away.
2. 5 minutes of loitering above the airport.
3. 5% of the block fuel as contingency.

In addition to running simulations to determine the maximum range of the aircraft, this study ran missions representative of current routes flown by the reference aircraft. All routes flown by the aircraft in 2019 were collected (Graver et al., 2020) to determine the median and 90th percentile route lengths. For the ATR 72, 50% of the missions were < 400 km long and 90% of the missions were < 750 km long.

APPENDIX C: HYDROGEN COST ESTIMATION

For this work, hydrogen is assumed to be produced onsite. The cost of green hydrogen is broken into three components:

1. Cost of hydrogen production.
2. Cost to liquify or compress the hydrogen.
3. Cost of the hydrogen refueling station (European Commission, 2021).

It is assumed that the infrastructure for green hydrogen production will be on site at airports and no transportation will be required. Zhou et al. (2022) considered the hydrogen production costs from both, direct- and grid-connected hydrogen production and chose the cheaper option at a sub-regional basis in the United States and EU (see Table A3).[13] These are average costs across entire regions, while choosing the minimum mode of production across electrolyzer type and energy source (Zhou et al., 2022). This study also assumes a 1 MW input power production plant which produces 500 kg/day of hydrogen (Zhou & Searle, 2022). That would be enough hydrogen to fuel about 3 flights in a day.

Table A3. Estimate of green hydrogen production cost in 2020 USD per kg of hydrogen

Year	United States	European Union
2030	3.1	4.7
2050	1.6	3.2

The cost of liquefaction and compression is based on the energy required. A compression energy requirement of 6 kilowatt-hours per kilogram of hydrogen and a liquefaction energy requirement of 12 kWh/kg H_2 is used (U.S. DOE, 2009). For energy prices, ICCT's estimate for the levelized cost of renewable energy is used with additional charges for transmission and distribution. It is assumed that the energy comes from the grid with taxes and surcharges to use renewable energy, and not just the grid-averaged energy mix (Zhou et al., 2022). Electricity prices, broken down by levelized cost for the electricity (LCOE) and the price with charges included for transmission and distribution (T&D), are shown in Table A4.

Table A4. Estimated annual renewable energy price in the United States and EU in 2020 USD per MWh

Year	United States		European Union	
	LCOE	LCOE + T&D	LCOE	LCOE + T&D
2030	28	77	51	97
2050	21	72	41	88

13 Direct connection requires hydrogen production to be directly connected to a renewable energy generator. This avoids grid transmission fees and taxes but limits the utilization rate of the hydrogen production plant. Grid connection has the hydrogen production plant connected to the grid. It avails of a higher utilization rate but pays a higher price for electricity which includes transmission costs and associated taxes. Zhou et al. (2002) found that direct connection is cheaper in most regions in the United States, while grid connection is cheaper in most EU countries. Land availability in the vicinity of airports is not considered when analyzing direct connection.

The hydrogen refueling station cost includes the cost of the compressor/liquefier, storage, and dispensing. The initial capital investment assumption for the refueling stations are shown in Table A5. The European Commission's estimates for a 2,000 kg/day refueling station are used for the EU capital cost estimate (European Commission, 2021).[14]

For the United States, a National Renewable Energy Laboratory (NREL) report estimates the capital investment required for an onsite electrolysis refueling station in 2025 based on the United States DOE's Hydrogen Analysis (H2A) case studies (Melaina & Penev, 2013). The cost of hydrogen production is subtracted to give a required capital investment of $1,625 per kg per day (in 2007 USD). This equates to a total capital investment of $4,175,000 in 2020 USD for a 2,000 kg/day refueling station in 2025. Researchers at Argonne National Laboratory suggest that the cost of a 1,000 kg/day refueling station in 2015 would be $3.4 million (Reddi et al., 2017). To extrapolate to a 2,000 kg/day refueling station, this analysis assumes a factor of 1.90 increase in absolute capital cost which accounts for 10% reduction in cost due to economies of scale. To extrapolate the cost of a refueling station in 2015 to 2025, this analysis assumes a 2% annual reduction in cost from 2015 to 2025. This results in an estimated capital investment of $5,750,000 in 2020 USD for a 2,000 kg/day refueling station in 2025. This is almost 40% higher than the cost estimated by Melaina and Penev (2013). To reconcile these, the average of the two, $4,940,000, is assumed to be the capital cost of a 2,000 kg/day refueling station in 2025. The cost reduction curves from the European Commission's report are used to estimate the capital investment required in 2030 and 2050.

Table A5. Estimated initial capital investment required for a 2,000 kg/day hydrogen refueling station in 2020 USD

Year	United States	European Union
2030	4,270,000	4,400,000
2050	3,750,000	3,860,000

For an LH_2 refueling station, the European Commission suggests adding €2,000,000 to the cost of a GH_2 refueling station. No time frame or cost decline is suggested. This study assumes €2,000,000 to be the cost in 2020 and assume a 2% reduction in cost every year until 2050. The same cost is assumed for the United States. The euro-to-dollar conversion uses the average conversion rate of 2020, €1 = $1.1422 (European Central Bank, 2023).

This study assumes an annual operational cost of maintenance and labor to be 4% of the initial capital investment. This is in line with the European Commission assumptions and those made by Zhou and Searle (2022) for the hydrogen production costs. This analysis includes a contingency factor of 1.2 on the total upfront capital investment to account for project design and construction at the beginning of the project.

To calculate the levelized cost of the refueling station, certain financial assumptions are required. These are listed in Table A6. The debt-to-equity ratio, return on equity, loan interest rate, and the corporate tax rate are used to calculate the weighted average cost of capital. This is adjusted by the inflation rate to give the discount rate for the project. This discount rate is used to calculate the net present value of the capital investment and operating costs over the 15-year lifetime of a hydrogen refueling station. The corporate tax rates are region-based (Organisation for Economic Co-

14 The 2,000 kg/day refueling capacity could service about 15 flights a day. The hydrogen refueling station is made bigger to support hydrogen transported from off-site production plants and to support future growth in production capacity should hydrogen fuel cell aircraft become more popular.

Operation and Development, 2023). For the EU, a GDP weighted average across all 27 countries is used.

Table A6. Financial assumptions for hydrogen refueling stations

Inflation rate	2%
Debt-to-equity ratio	60%: 40%
Return on equity	16%
Loan interest rate	4%
Corporate tax rate	EU: 25.28%, U.S.: 25.81%
Hydrogen refueling station Lifetime	15 years

Since it is unlikely a hydrogen refueling station would be used at 100% capacity, this study assumes a gradually increasing utilization factor up to a maximum of 80%. The utilization curve for the lifetime of the station is shown in Figure A1. The utilization rate would increase for a hydrogen refueling station in 2030 roughly mimicking the demand induced by the addition of one new fuel cell turboprop per year at an airport. For a hydrogen refueling station in 2050, this ramp up would be doubled, mimicking the addition of two new fuel cell turboprops per year.

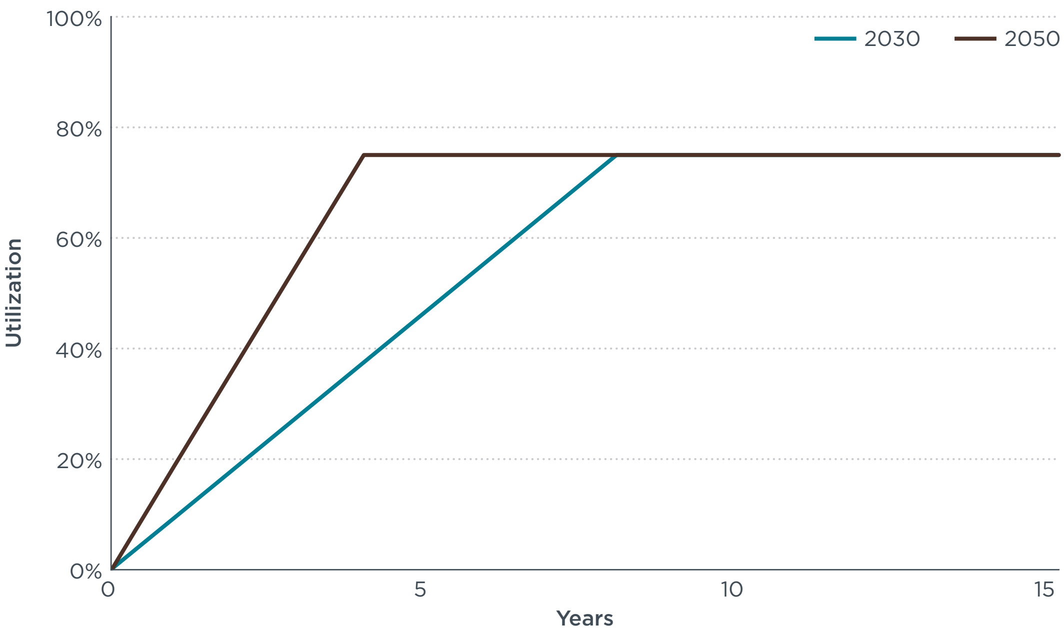

Figure A1. Utilization rate over the hydrogen refueling station lifetime.

Finally, to convert all cost values form 2020 USD to 2022 USD, a factor of 1.09 is used to adjust for the inflation (U.S. Bureau of Labor Statistics, 2021).