Published name
Emerging Technology Considerations for Autonomous Passenger Advanced Air Mobility (APAAM) Aircraft

Short comment
Autonomous Passenger Advanced Air Mobility (APAAM) refers to aircraft weighing less than 8635 kg (CS-23, FAA Part 23) that carry passengers without a pilot onboard and are controlled by a pilot or supervisor on the ground. The motivation for considering such aircraft is that they can achieve price-parity with fossil fuels for interstate and trans-continental air travel in the 2030 time frame, 20 years sooner than commercial aircraft are forecast to achieve similar price points using hydrogen or sustainable aviation fuel.. This submission describes the use case, infrastructure, and emerging technologies required for Australia to develop a net-zero APAAM capability for the 2030-2050 time frame.

Autonomous Passenger Advanced Air Mobility

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1 Introduction

Autonomous Passenger Advanced Air Mobility (APAAM) refers to aircraft weighing less than 8635 kg (CS-23, FAA Part 23) that carry passengers without a pilot onboard and are controlled by a pilot or supervisor on the ground. The motivation for considering such aircraft is that they can achieve price-parity with fossil fuels for interstate and trans-continental air travel in the 2030 time frame, 20 years sooner than commercial aircraft are forecast to achieve similar price points using hydrogen or sustainable aviation fuel. This submission describes the use case, infrastructure, and emerging technologies required for Australia to develop a net-zero APAAM capability for the 2030-2050 time frame. Benchmarking examples are included to provide credible estimates and comparisons to facilitate policy development and investment decisions in which APAAM may compete with other net-zero pathways.

2 Use Case Summary

Autonomous Passenger Advanced Air Mobility (APAAM) aircraft can provide interstate and transcontinental travel with zero emissions beginning in the 2030 time frame. APAAM aircraft are a distinguished use-case from manned advanced air mobility (AAM) aircraft because APAAM aircraft are uniquely suited to achieve price parity with commercial airline travel by 2030. By market size, Savion estimates APAAM will have an addressable market of $120 Billion per year from airline travel. By contrast, manned electric-vertical takeoff aircraft are now forecast to have a global market of $12 Billion per year. APAAM has specific infrastructure, and emerging technology needs which are summarized in this submission.

3 Infrastructure

APAAM aircraft need renewable airport charging, energy generation and bandwidth. When "bundled" with renewable airport charging, APAAM flights generate carbon credits that can be redeemed by businesses and exported to meet voluntary and involuntary offset obligations. Airports can generate additional revenue from APAAM by recycling the aircraft's batteries to store renewable energy. The stored energy can then be used to generate low-cost hydrogen or bio-methane for trans-continental flights.

3.1 Airport Fast Charging

Battery-powered APAAM aircraft will likely require "fast charging" to maximize revenue generation for inter-state flights. Unfortunately, the Australian grid is not powerful enough for fast charging for batteries onboard the aircraft can close the cab without costly grid modifications. The batteries onboard the aircraft can be removed annually and used for solar energy storage at designated airports. On average, each APAAM aircraft can generate 1 Australian Carbon Credit Unit (ACCU) per flight and 1 MWh of renewable energy storage per year of use.

3.2 Free-Hydrogen Zones

Airports that implement fast charging will have a source of low-cost electricity to produce hydrogen in what Savion terms "a free hydrogen zone". Hydrogen production and storage infrastructure can be stored under the solar farms that are creating energy for fast charging. The excess solar energy stored in the recycled battery can then be routed back to the hydrogen production infrastructure to make hydrogen with no additional electricity cost, hence the name "free hydrogen zone". The hydrogen can then be used in hydrogen-equipped APAAM aircraft for trans-continental flights that are at price parity with commercial airlines.

3.3 Free Bio-Methane Zones

Airports can maximize their revenue by using their waste streams (ie sewage) and excess electricity to create bio-methane for trans-continental flights. Anaerobic digesters, upgraders, and liquefiers can be installed which convert wastewater into bio-LNG. Anaerobic digestors extract the bio-methane from the waste stream. Upgraders increase the concentration of bio-methane gas to levels suitable for liquefaction. Liquefaction converts the bio-methane gas into bio-LNG which can be used on board aircraft for trans-continental travel. Bio-LNG will give APAAM aircraft their longest possible trans-continental range due to its superior volumetric-energy density to liquid hydrogen. Bio-LNG can be made to use existing gas turbines with a small combustor modification. Benchmark Bio-methane and Bio-LNG production projects include Jemina's wastewater project and the Altamont Landfill in Livermore, CA USA respectively. Benchmark bio-LNG flights include Savion's LNG flight demonstration in Livermore, CA USA in 2019. As of writing, Australia is the world's largest fossil LNG exporter. Injecting airport-made bio-LNG into these export streams can facilitate the export of Australian-made APAAM aircraft, APAAM flight credits, and APAAM carbon credits.

3.4 Bandwidth

Bandwidth reservations by federal agencies of 5G and satellite spectrum for APAAM flights can maximize safety and increase the volume of revenue-generate APAAM operations. Savion estimates that a minimum of 7 MB upload and 7 MB download will be needed per flight to facilitate pilot supervision and air traffic control integration. No UTM or changes to the air traffic control are needed for APAAM to enter service. Technologies such as synthetic voice and sensor health can be used to provide verbal communication and reach the level of flight control safety required for autonomous passenger travel.

4 Emerging Technologies

Australia's development of the MQ-28 "GhostBat" proves that Australia possesses the talent, emerging technology and production methods to build civilian APAAM aircraft of similar size. Civilian APAAM aircraft are currently forecast to enter service in 2028 in the United States and receive certification in China in 2023. These "early adopter" vertical-takeoff APAAM aircraft are capable of short-range inter-city transport only. Australia can conduct targeted development of long-range Blended Wing Body (BWB) airframes, lithium-air batteries, and cryogenic storage to deliver APAAM aircraft capable of interstate and trans-continental travel in the 2030 timeframe. The foundational technology for each of the three emerging technologies has been demonstrated in the lab setting and the case of the BWB, has undergone extensive flight testing are therefore at a high technology readiness level.

4.1 Blended Wing Body (BWB) Airframes

BWB airframes are "flying-wing" airframes that "blend" the wing and fuselage together to achieve a higher aerodynamic efficiency and higher internal volume. The combination of higher internal volume and high aerodynamic efficiency can facilitate the efficient use of zero-emissions fuels, all of which require more volume than fossil fuels. The efficient integration of zero-emissions fuels facilitated by BWBs enables APAAM aircraft to go beyond the inter-city range and provide service for inter-state and trans-continental routes.

4.2 Lithium-Air Batteries

Lithium-Air batteries achieve energy densities (2000 Wh/kg) over 5 times higher than today's batteries by creating an electrical circuit with the outside air similar to a hydrogen fuel cell. When integrated into an aircraft, lithium-air batteries can match the range provided by a compressed hydrogen power train while retaining an infrastructure cost advantage of requiring only electricity to charge. Stanford University recently published a design for a lithium-air powered aircraft that can match the speed, range, and payload of a commercial aircraft. In 2023, the University of Illinois demonstrated a lithium-air battery cell with an energy density of 1000 Wh/kg lasting 1000 cycles. More alarmingly, the University of Illinois predicted entry into service of lithium-air batteries by 2033, roughly the same time as compressed hydrogen aircraft. Lithium-air batteries therefore have the potential to undercut Australia's considerable investment in hydrogen production infrastructure for air transport. Australia is however well positioned to develop and produce its own Lithium-Air batteries by mobilizing its previous investment in Deakin University's "Batteri Hub" to develop Lithium-air batteries in addition to lithium-metal batteries that are the current state of the art. To be clear, APAAM aircraft can achieve inter-state travel with currently available battery chemistry.

4.3 Lightweight Cryogenic Energy Storage

Lightweight cryogenic storage of liquid hydrogen and Bio-LNG can facilitate trans-continental flights on APAAM aircraft. The most recent hydrogen technology review stated that the weight of current long-lasting cryogenic storage tanks is prohibitive for practical interstate travel. Cryogenic rocket tanks have exceeded the threshold but only last for a few flights and would thus be cost-prohibitive to implement in an aircraft operation. In addition to these challenges, Savion discovered during its flight testing that cryogenic pumps are required to elevate vaporized cryogenic fuels to the pressures needed by fuel cells and gas turbines to generate propulsion. Purpose-built composite cryogenic tanks with metal lining can be designed to fit the proportions of BWB airframes and last long enough for practical air service use.

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Hydrogen-powered aircraft: Fundamental concepts, key technologies, and environmental impacts

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ABSTRACT

Civil aviation provides an essential transportation network that connects the world and supports global economic growth. To maintain these benefits while meeting environmental goals, next-generation aircraft must have drastically reduced climate impacts. Hydrogen-powered aircraft have the potential to fly existing routes with no carbon emissions and reduce or eliminate other emissions. This paper is a comprehensive guide to hydrogen-powered aircraft that explains the fundamental physics and reviews current technologies. We discuss the impact of these technologies on aircraft design, cost, certification, and environment. In the long term, hydrogen aircraft appear to be the most compelling alternative to today's kerosene-powered aircraft. Using hydrogen also enables novel technologies, such as fuel cells and superconducting electronics, which could lead to aircraft concepts that are not feasible with kerosene. Hydrogen-powered aircraft are technologically feasible but require significant research and development. Lightweight liquid hydrogen tanks and their integration with the airframe is one of the critical technologies. Fuel cells can eliminate in-flight emissions but must become lighter, more powerful, and more durable to make large, fuel cell-powered transport aircraft feasible. Hydrogen turbofans already have these desirable characteristics but produce some emissions, albeit much less damaging than kerosene turbofans. Beyond airframe and propulsion technologies, the viability of hydrogen aircraft hinges on low-cost green hydrogen production, which requires massive investments in the energy infrastructure.

1. Introduction

Aircraft are the only vehicles that can transport people and goods across the world within one day. In 2016, aviation drove $2.7 trillion in economic activity and supported 65.5 million jobs, which made up 3.6% of the global gross domestic product (GDP) [1]. Civil aviation also catalyzes economic growth in developing markets by increasing their access to the global economy.Aircraft efficiency has doubled since the dawn of the jet age thanks to technological breakthroughs and continuous incremental improvements [2]. Compared to other forms of transportation, there is much more of an incentive to reduce the fuel consumption of aircraft because added weight requires increasing lift, which in turn increases drag, further increasing the fuel required. This incentive is why aircraft have been at the forefront of innovations in structures, materials, aerodynamics, control systems, propulsion, operations, and engineering design methods.

However, aviation currently relies on fossil fuels, and its emissions are responsible for 3.5% of climate warming caused by humans [3]. This percentage is bound to increase because aviation is one of the most challenging sources to decarbonize. Given the long development time of aircraft and slow fleet turnover rate, there is an immediate need to develop new aircraft with drastically lower climate impact.

Hydrogen-powered aircraft emit no carbon dioxide and would reduce or eliminate other emissions while maintaining existing routes. Interest in these aircraft is currently high, but hydrogen aircraft present technical and economic challenges. Handling and storing hydrogen is challenging, particularly as a liquid. Designing hydrogen propulsion systems is also a new challenge. The cost of new aircraft and infrastructure would be significant. Additionally, the price of renewable hydrogen would need to be competitive. These technical and economic factors, along with inertia in the aircraft industry, may slow the transition to hydrogen aircraft.

It is not the first time that hydrogen aircraft have gained interest. In the 1950s, the United States government investigated hydrogen as a fuel to increase the performance of high-altitude reconnaissance aircraft [4,5]. It funded the Lockheed CL-400 Suntan project, a Mach 2.5 reconnaissance aircraft. This project and others around the same time included modeling and experimental studies to investigate hydrogen propulsion, fuel systems, storage, and safety. However, the combination of falling short in range estimates and concerns from government

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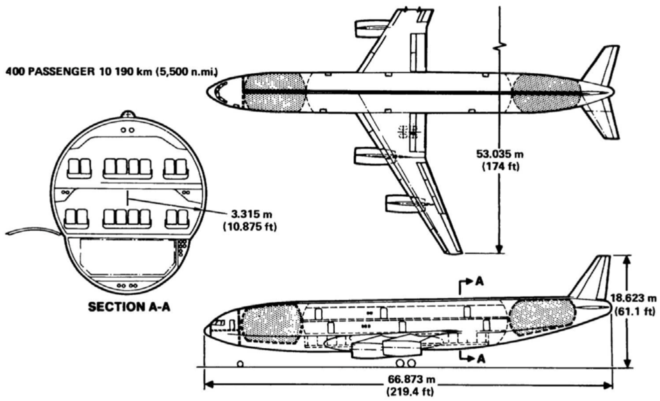


Fig. 1.1. In the 1970s, hydrogen aircraft gained interest because of the oil crisis. NASA contracted Lockheed to investigate the feasibility of a range of hydrogen aircraft concepts, one of which is shown here.
Source: Reproduced from Brewer et al. [9].

funding agencies ended the project. In the 1970s, the oil crisis spurred interest in commercial transport aircraft powered by alternative fuels [6]. Lockheed was funded again, this time by NASA, to investigate using hydrogen to fuel subsonic and supersonic transport aircraft [7,8]. Fig. 1.1 shows one of the concepts. However, the oil crisis waned, and the designs were not pursued further.

Aviation's impact on climate change is driving renewed interest in hydrogen aircraft. Climate change is a long-term and global problem, so this interest might be here to stay. The European Commission-funded Cryoplane project [10], which began in 2000, was the first large-scale project investigating the feasibility of hydrogen aircraft with the motivation of reducing climate impact. In the past decade, the aircraft design community has pursued an array of government- and privately-funded hydrogen aircraft projects and the pace of these projects is accelerating.

Airlines run on slim profit margins, and new commercial airplane programs are costly and risky. Some researchers expect that hydrogen aircraft need government incentives or regulations penalizing conventional aircraft to overcome the industry's inertia and make an economically-compelling case for airlines [11]. However, there may be scenarios where hydrogen aircraft are economically advantageous in the long run.

From a technological perspective, hydrogen-powered aircraft could look similar to today's aircraft and fly similar missions. The most significant changes involve accommodating the hydrogen storage and the new fuel system. A similar approach to today's aircraft would leverage existing design tools and technologies. Alternatively, hydrogen opens possibilities for new technologies, including fuel cells, enabling new configurations and capabilities, such as distributed electric propulsion.

This paper provides the background for readers to play an informed role in the budding hydrogen-powered aircraft industry. We explain the fundamental physics that drives key hydrogen aircraft technologies and review the current state-of-the-art for those technologies. We also describe how those technologies affect the overall aircraft design. Finally, we outline the cost, certification, and climate consequences of hydrogen aircraft.

2. The case for hydrogen aircraft

Current transport aircraft are well-optimized. Aircraft manufacturers and airlines continue decreasing fuel burn per seat mile through composite materials, advanced engine technologies, aerodynamic refinement, and improved operational efficiency. However, the continued increase in demand for air transportation is expected to outpace the rate of efficiency improvement. Fig. 2.1 shows that the predicted overall

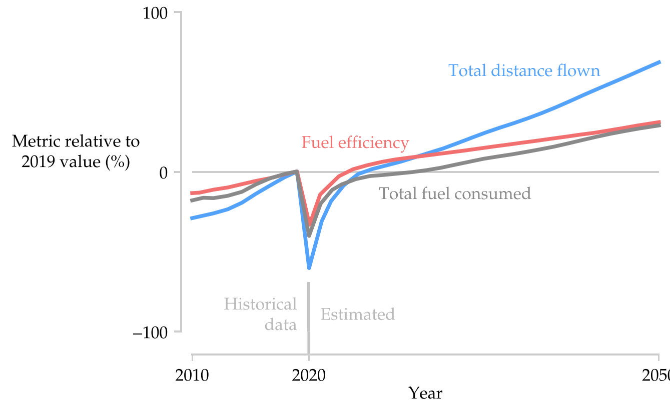


Fig. 2.1. The demand for passenger air travel outpaces increased aircraft efficiency, so energy consumption is projected to increase through 2050.
Source: Data from U.S Energy Information Administration [12].

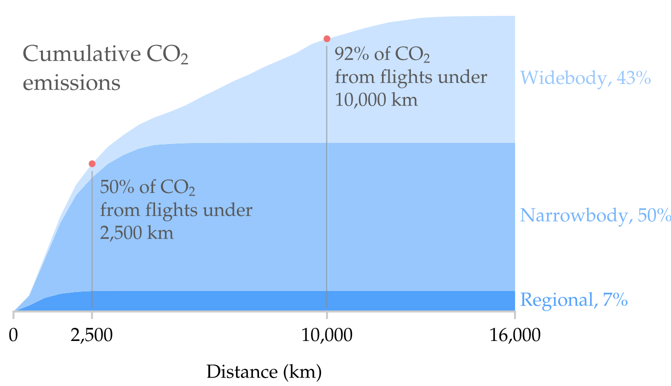


Fig. 2.2. Cumulative CO_2 emissions from passenger aviation in 2019.
Source: Data from Graver et al. [21].

energy consumption of passenger air travel in the U.S. will continue to increase despite efficiency improvements [12]. Similar trends exist globally. The COVID-19 pandemic caused the passenger distance flown to plummet in 2020, but the recovery was swift [13].[1]

The vast majority of commercial aviation's emissions come from narrowbody and widebody aircraft, as shown in Fig. 2.2. Full-electric aircraft powered by batteries can potentially eliminate direct emissions from short-haul regional routes in the coming decade. However, most commercial flights cannot be replaced by full-electric aircraft because the specific energy (energy per mass) of batteries is far too low [15,16]. The specific energy of batteries is currently about 50 times lower than that of kerosene. Filling the entire fuselage of a Boeing 737 with batteries would only allow it to fly for one hour [17]. Advanced battery chemistries, such as lithium-air, may increase the specific energy by an order of magnitude. However, they still require considerable development to increase their power density, cycle life, and other critical properties [18–20].

There are two schools of thought for drastically reducing aircraft emissions. One advocates using hydrocarbon fuel with reduced lifecycle emissions compared to fossil fuel called *sustainable aviation fuel* (SAF). Using SAF requires only minimal changes to existing aircraft, so it is also known as a *drop-in fuel*. The other school of thought advocates fuels that do not emit any carbon in use, such as hydrogen or ammonia.

[1] The efficiency also decreased temporarily because of lower passenger load factors, as airlines blocked off middle seats, struggled to sell tickets, and, in some cases, operated empty flights to maintain airport slots [14].

SAFs, are hydrocarbon fuels whose production partially offsets the carbon dioxide emitted during flight. This includes fuel derived from plants (biofuels), used cooking oil, waste, and other sources. SAFs are convenient because they can power existing aircraft with minimal or no modifications, offering a solution for near-term emission reduction. SAFs are more expensive than conventional jet fuel, which would increase the aircraft operating cost [22]. Furthermore, SAFs are unlikely to reach net-zero lifecycle emissions, optimistically reducing the climate impact of flying by 60% [23]. Farming the feedstock and chemically synthesizing fuel produce greenhouse gases that prevent SAFs from achieving net-zero lifecycle emissions [24]. Vast amounts of farmland are needed to grow the feedstock. To create new farmland, farmers can plow existing forests or grasslands. The plowed plants and soil release CO_2 as they are decomposing or are burned [25]. Those plants were already absorbing CO_2, which further hinders the emissions reductions [22]. These changes to the land are called *land use emissions*. Laborde [26] estimates that in Europe, they would cut the benefits of SAFs versus conventional fossil fuels in half. Lark et al. [27] find that the carbon intensity of corn ethanol biofuel is at least as high as gasoline, if not higher, largely because of land use change estimates. Another type of SAF is *electrofuel* (also known as *e-fuel*, or *synfuel*). To produce electrofuel, electrolysis and carbon capture powered by renewable electricity generate hydrogen and carbon dioxide, which are then used to create hydrocarbon fuels through chemical synthesis [28]. Electrofuel requires nearly three times the amount of energy to produce and distribute per unit of energy stored than hydrogen and is expected to be more costly [23].

Hydrogen can be produced using water and renewable electricity via electrolysis. Ammonia can be produced by combining hydrogen with nitrogen from the air via chemical processes [29,30]. Ammonia's energy per weight is one sixth of hydrogen's and half of kerosene's, so it is not favored for aviation applications. Since these fuels do not contain carbon, using them produces no carbon dioxide. However, clean sheet aircraft designs are necessary to reap the benefits of these fuels, primarily because of their different storage properties, energy densities, and propulsion system requirements compared to kerosene.

While they can help reduce the climate impact of existing aircraft, SAFs are not the best long-term solution because they cannot achieve zero CO_2 emissions, require large amounts of land, and are costly. Hydrogen fuel cell aircraft can reach true zero-emission during operation. Hydrogen combustion aircraft eliminate CO_2 emissions and reduce other emissions. Hydrogen aircraft are predicted to be the least expensive and most sustainable way to fly without carbon [31]. Airbus has stated that hydrogen propulsion is the technology with the lowest cost per ton of CO_2 avoided compared to all other options for decarbonizing air transportation.[2] Depending on how optimistic the assumptions are, hydrogen aircraft may also be lighter, use less energy, and have lower operating costs than current kerosene-powered aircraft by taking advantage of hydrogen's high specific energy [7,9,32].

Hydrogen is a potential solution for other hard-to-decarbonize industries. Besides aviation, the most challenging industries to decarbonize are shipping, iron, steel, and cement production [33]. In 2016 these industries made up 14% of global greenhouse gas emissions (CO_2eq). Hydrogen and biofuels are two of the most promising solutions to reduce the climate impact of steel and cement production [34] and have the potential to power rail and marine applications [35–37]. This further incentivizes developing infrastructure for producing and distributing renewable hydrogen to take full advantage of economies of scale.

For these reasons, hydrogen aircraft have gained traction in industry and government projects. In the near term, Universal Hydrogen (shown in Fig. 2.3) and ZeroAvia are independently retrofitting existing turboprop aircraft with hydrogen fuel cell propulsion systems to serve regional markets beginning around 2025. H2FLY, bought by Joby Aviation in 2021, is flight-testing its hydrogen fuel cell-powered HY4 demonstrator to develop a hydrogen propulsion system for small to regional aircraft (Fig. 2.4). In the longer term, Airbus announced its ZEROe project in 2020 to develop clean sheet commercial hydrogen aircraft [49], shown in Fig. 2.5. In Europe, the government-funded FlyZero project [50], the Clean Sky 2 Joint Undertaking [23], and the Clean Aviation Joint Undertaking [51] have focused on developing an array of hydrogen aircraft concepts and technologies.

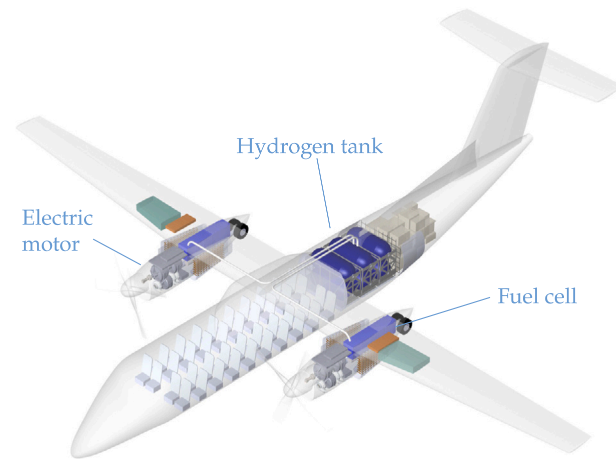


Fig. 2.3. Universal Hydrogen's turboprop fuel cell retrofit concept (Universal Hydrogen image).

Fig. 2.4. H2FLY began flight testing its HY4 aircraft in 2016 (H2FLY GmbH image).

Fig. 2.5. Airbus' ZEROe hydrogen-powered turbofan concept (Airbus image).

[2] https://youtu.be/8oh5PfVtwz8?t=2327, accessed 24 August 2021.

Table 2.1
Large hydrogen-powered aircraft that have flown.

Aircraft	First flight	Storage	Propulsion	Notes	Source
NACA-modified B-57	1957	LH_2	Turbojet	One hydrogen-powered engine	Sloop [4]
Tupolev Tu-155	1988	LH_2	Turbofan	One hydrogen-powered engine	Sosounov and Orlov [38]
Boeing Fuel Cell Demonstrator Airplane	2008	GH_2	PEMFC	Fuel cell provided all power in cruise	Boeing [39]
Antares DLR-H2	2009	GH_2, 350 bar	33 kW fuel cell		German Aerospace Center [40]
AeroVironment Global Observer	2011	LH_2			AeroVironment [41,42]
Boeing Phantom Eye	2012	LH_2	Modified Ford 2.3L ICE		Boeing [43]
H2FLY HY4	2016	GH_2	45 kW PEMFC		German Aerospace Center [44]
ZeroAvia Piper Malibu demonstrator	2020	GH_2, 350 bar	PEMFC	Only partially fuel-cell powered	Harris [45], Warwick [46]
ZeroAvia Dornier 228 demonstrator	2023	GH_2	Fuel cell	Batteries and fuel cell each powered half of left propeller with stock right engine	Crownhart [47]
Universal Hydrogen Dash-8 demonstrator	2023	GH_2	Megawatt-class PEMFC	Fuel cell powered right engine with stock left engine	Norris [48]

While there is much excitement surrounding hydrogen aircraft, only a few have flown. None have been used regularly by commercial operators or governments (at least based on public knowledge). Table 2.1 lists human-scale hydrogen aircraft that have been flight tested. The frequency of hydrogen aircraft's first flights has increased in recent decades, but most are still small, one-off demonstrators. Experimental flight testing would need to increase substantially to make hydrogen aircraft viable in the near future.

3. Hydrogen aircraft design

Using hydrogen as a fuel involves different design challenges and active constraints compared to conventional kerosene-powered aircraft. The differences are primarily due to hydrogen's substantially higher specific energy (energy per unit mass) and unique storage challenges because of its lower energy density (energy per unit volume).

Hydrogen must be stored as a compressed gas or cryogenic liquid to achieve practical energy densities. Table 3.1 lists the specific energy and energy densities of kerosene (Jet A-1), cryogenic liquid hydrogen (LH_2), and gaseous hydrogen (GH_2) at two different pressures. The highest energy density for hydrogen is obtained for liquid hydrogen storage, but it is still four times lower than kerosene's. Hydrogen storage requires specialized tanks that incur a weight penalty relative to kerosene storage. The tank efficiency in Table 3.1 quantifies this penalty; we define it in Section 4. Highly compressed hydrogen requires pressure vessel tanks, often cylindrical, to carry the pressure loads. Liquid hydrogen (LH_2) storage requires a heat management system. The heat from the environment entering the LH_2 (called *heat leak*) causes the liquid to boil. This is called *boil-off* and increases pressure in the tank. If the pressure reaches the tank's structural limit, the hydrogen must be vented, which wastes fuel. To avoid this waste, tanks can be designed to withstand greater pressures, insulate better, or both. To reduce heat leak, cryogenic tanks are most efficient when they have a low surface area-to-volume ratio, so the closer to a sphere, the better.

Low surface area-to-volume ratio tank shapes do not fit well into aircraft wings, so they are usually placed in the fuselage or dedicated fuel pods. Both external fuel pods and additional fuselage space increase the aircraft's wetted area, increasing aerodynamic drag. Removing the fuel from the wings eliminates the structural load alleviation benefit, which may increase the wing's structural weight. Thus, hydrogen storage incurs drag and weight penalties [32,55].

As previously mentioned, hydrogen's energy density is about four times lower than kerosene's; however, its energy per unit mass is nearly three times *greater*. For the same amount of energy required to fly, the weight of hydrogen needed is a third of the weight of the required kerosene. If there were no weight or drag penalties, this would mean a lower takeoff weight and, thus, a smaller wing, particularly for an aircraft with a high fuel fraction (the fuel weight divided by the aircraft's total takeoff weight). Because of the cyclical dependence in the aircraft sizing procedure, a smaller wing further reduces the aircraft drag and structural weight, reducing the takeoff weight, and so on.

However, as already mentioned, there are weight or drag penalties due to the hydrogen storage tanks' added weight, volume, and packaging. Based on previous design studies, it is still unclear whether the net effect of higher energy per unit mass and storage penalties would be to increase or decrease in the energy used for a given flight [32,56]. Verstraete [57] predicts that for large long-haul aircraft, the takeoff weight is reduced by 25% and total energy reduced by 15% compared to a kerosene aircraft. For a similar design mission, the Cryoplane study [56] found a takeoff weight decrease of only 14.8% and a total energy *increase* of 9%. The Cryoplane project aimed to retrofit an existing aircraft rather than design a new one, potentially explaining the differences. As the fuel fraction decreases, so do the takeoff weight savings, potentially becoming a weight increase for small aircraft [56].

The decrease in fuel weight due to hydrogen's high specific energy affects the active constraints in the aircraft's design. A certain amount of energy is required for the aircraft to climb to the cruise altitude. The hydrogen required to provide that energy is roughly one-third of the mass of the required kerosene. This means that a hydrogen aircraft loses less weight in climb than a kerosene aircraft. The higher weight at the end of the climb phase may require more thrust relative to the takeoff thrust. Thus, the top-of-climb thrust requirement is more likely to be an active constraint on the engine design if it is not already active. Secondly, the weight decrease during cruise is lower, so the ideal cruise altitude increases more slowly. This means smaller altitude step climbs or no step climbs at all.

From an operating cost perspective, the high specific energy of hydrogen and lighter takeoff weight may result in lower energy usage for large long-haul flights compared to kerosene [57] (as mentioned, this is in contrast to the Cryoplane study [56]). For smaller, shorter-range aircraft, the same may not be true. The complexity and performance

Table 3.1
Properties of liquid (LH_2) and gaseous (GH_2) hydrogen [52–54] and approximate tank gravimetric efficiencies (higher indicates a lighter tank). Specific energies are given as the lower heating value (LHV). In some cases, more energy than the LHV dictates may be extracted by condensing water vapor in the exhaust (see Section 5.2.6).

Property	Jet A-1	LH_2	GH_2 (350 bar)	GH_2 (700 bar)
Specific energy (MJ/kg)	43.2	120	120	120
Energy density (MJ/L)	34.9	8.5	2.9	4.8
Storage temperature (K)	Ambient	20	Ambient	Ambient
Storage pressure (bar)	Ambient	~2	350	700
Tank gravimetric efficiency (%)	100	~30–90	1–15	1–15

penalty of hydrogen storage will likely increase the operating cost. Because of their added complexity, hydrogen tanks and airframes are expected to have higher maintenance and acquisition costs. The tank integration with the airframe adds drag, whether using pods or the fuselage. Verstraete [32] predicts that for large long-haul aircraft, these effects would result in a net decrease in direct operating cost, assuming hydrogen is at cost parity with kerosene on a per-unit energy basis (reasonable expectations for the cost of hydrogen are discussed further in Section 8). The Cryoplane study [56] found that the cost of hydrogen per unit of energy would need to fall to match that of kerosene for the two aircraft to have the same operating cost. The study predicted that this would happen around 2040.

4. Storage

Hydrogen has an extremely low volumetric energy density at ambient temperature and pressure. If the energy that a Boeing 777-200ER carries in kerosene were stored as hydrogen at ambient temperature and pressure, the required volume would correspond to about 500 fuselages of this aircraft. To reduce the required volume, the hydrogen can be compressed as a gas or cooled to make it liquid. If the hydrogen is compressed to 700 bar, the volume would reduce to a single Boeing 777-200ER fuselage. As a liquid, it would be half of that. These calculations do not include redesigning the aircraft to account for weight and fuel volume changes, but they give an idea of the required volume.

The specialized tanks to store hydrogen as a compressed gas or cryogenic liquid result in added weight. An important performance metric to assess the storage efficiency of a tank is *gravimetric efficiency* (also known as *mass fraction*), defined as

$$\eta_{\text{tank}} = \frac{W_{H_2}}{W_{H_2} + W_{\text{tank}}}, \quad (1)$$

where W_{H_2} is the weight of hydrogen the tank can hold and W_{tank} is the weight of the empty tank. The gravimetric efficiency is the fraction of the storage system weight taken up by fuel when it is full—the higher, the better. While this tank metric does not represent the *volumetric* efficiency, it quantifies the weight penalty incurred by using a given hydrogen storage solution. The gravimetric efficiency of kerosene tanks is 100% because they are integral to the wingbox structure and thus do not incur additional weight.

Tank gravimetric efficiency dramatically affects the design trades and benefits of hydrogen-powered aircraft. Tank gravimetric efficiency explains why some researchers say that hydrogen is feasible only for short- and medium-range aircraft, while others say that hydrogen is increasingly beneficial with increasing range. Fig. 4.1 shows how a hydrogen aircraft's fuel energy usage compares to that of a kerosene aircraft with varying tank gravimetric efficiencies and mission ranges. For low gravimetric efficiencies, hydrogen aircraft performance worsens relative to kerosene aircraft the longer the range. The assumption of a lower tank gravimetric efficiency is why some say hydrogen is only suitable for short- and medium-range aircraft. However, when the tank gravimetric efficiency is high, the opposite trend is observed: hydrogen aircraft improve over conventional kerosene aircraft as the range increases. The tipping point where the trend flips is around a tank gravimetric efficiency of 55%, regardless of the mission range. These trends align with energy usage in concepts published by Mukhopadhaya and Rutherford [58], Verstraete [32], and Brewer and Morris [7].

Fig. 4.2 shows a range of existing and proposed hydrogen tanks, illustrating the relationship between their gravimetric efficiency and the density of the hydrogen storage. The ideal point is as high and to the right on the plot as possible (gravimetric efficiency of 100% and hydrogen density as high as possible) because it means lower tank weight and smaller onboard storage. At first glance, LH_2 seems like the obvious solution. Its gravimetric efficiency is far greater, and the storage density is nearly twice that of compressed hydrogen. This conclusion is often true for large aerospace vehicles with high fuel fractions because they tend to be highly weight-sensitive. However, storing LH_2 adds complexity, which may not be worthwhile for smaller aircraft. This complexity is discussed in Section 4.2.

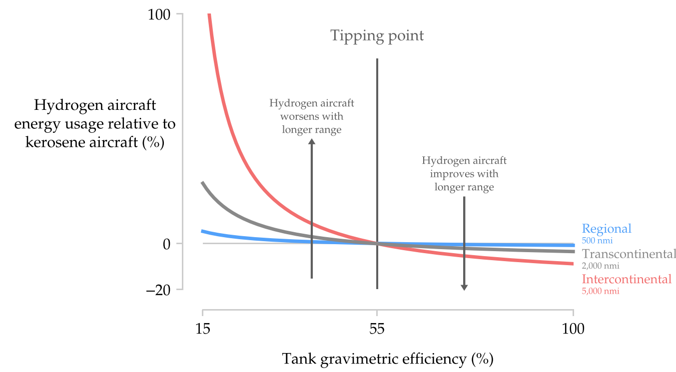


Fig. 4.1. Depending on the tank gravimetric efficiency, hydrogen might be feasible only for short and medium ranges or might improve as the mission range increases. The tipping point between these opposing trends is a tank gravimetric efficiency of around 55%.[3]

In Fig. 4.2, there are underlying trends that explain variations in certain tanks. For example, the Space Shuttle used its fuel orders of magnitude more quickly than Boeing's Phantom Eye, and the Shuttle's LH_2 tank was far larger. These effects enable higher gravimetric efficiency (less insulation needed and scaling properties work in the Shuttle's favor). However, the Shuttle's tank could never be used on an aircraft because of its high boil-off rate and single-use nature. For this reason, the plot offers only an idea of what can be expected from certain storage types.

Another challenge with hydrogen storage is hydrogen embrittlement and permeation. Embrittlement drastically decreases the material yield stress and ductility [64–66]. Materials, particularly metals, can become embrittled under tensile stress and hydrogen exposure. Permeation occurs because the hydrogen molecules are so small that some of them make their way through tank wall [64]. To give a sense of reasonable permeation rates, launch vehicle LH_2 tanks allow relatively high permeation losses of about 0.25% of the tank volume during ascent and orbital insertion [67]. Embrittlement and permeation are challenges in compressed and cryogenic storage, as explained in Sections 4.1 and 4.2, respectively.

4.1. Compressed

Compressing hydrogen to high pressures is one way of increasing hydrogen's density for onboard storage. Compressed GH_2 tanks operate at ambient temperatures, which requires much less active management than LH_2. GH_2 tanks can sit for extended periods without needing to be vented or refilled. These factors reduce the complexity of airplane fuel management.

The downside of compressed hydrogen is that it requires heavy pressurized tanks to withstand the high pressure safely. These tanks have low gravimetric efficiencies, seen in Fig. 4.2. The efficiencies are 1%–10% for most tanks, though it may be possible to achieve 10%–20% with advanced design and manufacturing techniques. Furthermore, compressed GH_2 storage is less space efficient than LH_2 storage.

Table 4.1 lists five categories of pressure vessels for compressed GH_2 storage. Type IV and Type V composite tanks (carbon or glass fiber

[3] Estimates are based on the Breguet range equation. We assume a thrust-specific energy consumption based on the GE90 [59] turbofan and Mach 0.8 cruise at 35,000 ft. The lift-to-drag ratio is assumed to be 20. Tank weight is added to the base zero fuel weight. We found that the tipping point of 55% is insensitive to these parameter values. However, using different lift-to-drag ratios for the hydrogen and kerosene concepts could shift it.

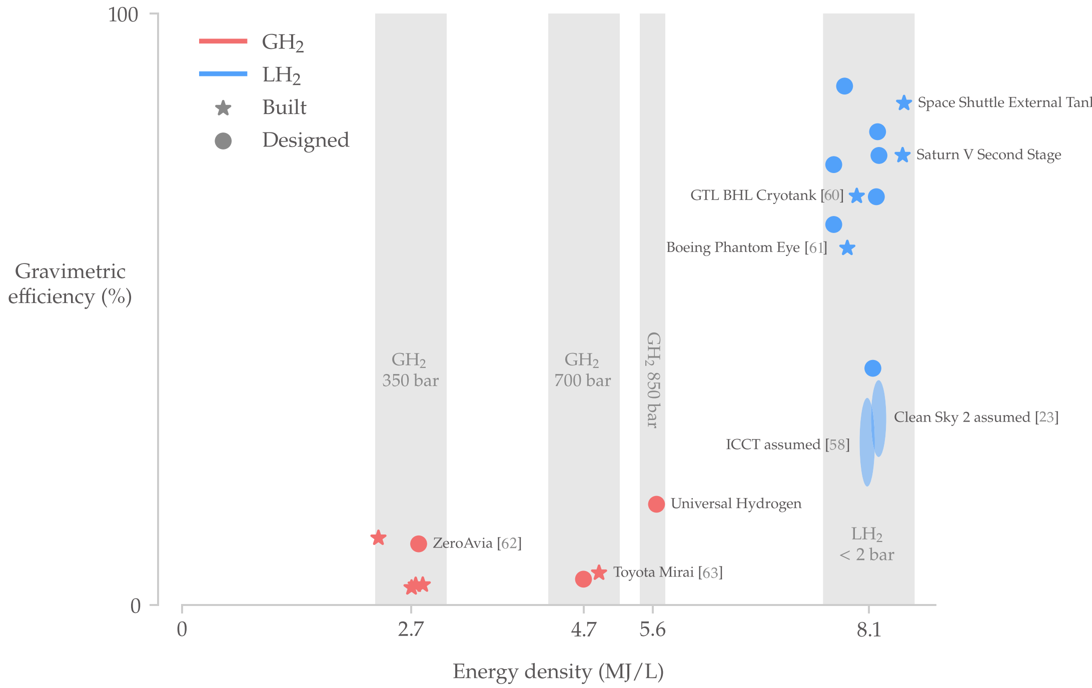


Fig. 4.2. Gravimetric efficiencies (as defined by Eq. (1)) of proposed designs and existing tanks. Realistic gravimetric efficiencies of LH_2 tanks are still uncertain; evolutionary improvements are predicted to be 25%–40% and revolutionary improvements 70% or more (see Refs. [23,58,60–63]).

Table 4.1
Materials and approximate gravimetric efficiency for pressure vessel types [72–74]. The most promising composites to reduce weight are carbon or glass fiber reinforced.

Tank type	Construction	Gravimetric efficiency
I	All metal	1%–2%
II	Mostly metal with some fiber composite overwrap	2%
III	Composite tank with metal liner	4%
IV	Composite tank with polymer liner	5%
V	Linerless composite tank	6%

reinforced) offer the best gravimetric efficiency, achieving one-fifth of the weight of steel and half of the weight of aluminum tanks [68]. Universal Hydrogen, a startup developing hydrogen tanks and conversion kits for existing aircraft, is seeking further weight reduction by removing the resin from the carbon fiber structure [69], shown in Fig. 4.3; it reports gravimetric efficiencies of 17% using this technique (the company now appears to be focusing more on liquid hydrogen storage development).[4] Modeling and experimental research to characterize the permeability of polymer liners and their related failure modes for Type IV tanks is ongoing [70,71].

Another vital weight consideration is the balance of plant, which refers to the necessary auxiliary tank components other than the tank itself. This system includes pressure regulators and valves. Lightweight and reliable balance of plant components are essential for gravimetrically-efficient tanks [72]. The drawback of lightweight composite tanks is the cost; the composite layer makes up 40%–80% of the total tank cost [68].

When considering metal as a material for compressed GH_2 tanks, it is essential to consider hydrogen embrittlement [66]. Metal is prone to hydrogen embrittlement under high tensile stress and when in contact with high-pressure hydrogen. The risk of embrittlement is particularly high at temperatures near or just below room temperature. These are temperatures experienced regularly by passenger aircraft, further increasing the required safety factor for metal hydrogen tanks [66].

Fig. 4.3. Universal Hydrogen reduced its composite GH_2 tank weight by removing the resin (Universal Hydrogen image).

The design of these tanks is nearly always cylindrical because circular cross sections improve structural efficiency for supporting pressure loads. The cylinder's end caps tend to be hemispherical, torispherical, or ellipsoidal. A hemisphere is the theoretical ideal shape, but it is costly to manufacture because forming flat sheets of metal into a hemisphere is challenging. Therefore, torispherical and ellipsoidal ends are the most common [68]. Manufacturing hemispherical end caps may be easier when using composite materials.

McLaughlan et al. [75] provide a qualitative overview of composite overwrapped pressure vessels (COPV), which are lightweight relative to other GH_2 storage solutions. Colozza [76] presents a simplified analysis method for sizing GH_2 tank wall thickness. Netting analysis [77,78] is an analytical technique for fiber-reinforced composite analysis that ignores the polymer matrix and assumes the fibers carry all the loads. This technique is well-suited for first-order pressure vessel analysis. It offers higher fidelity for analyzing fiber directions and layers than

[4] https://youtu.be/fsN90HSglxc?t=53, accessed 21 November 2022.

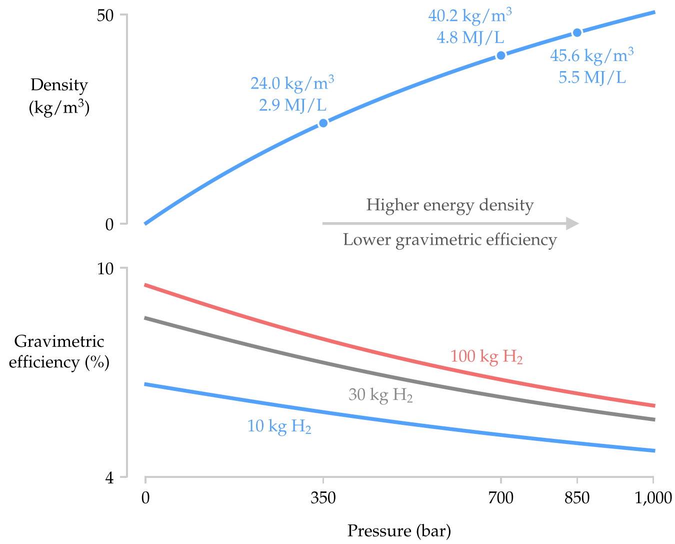


Fig. 4.4. For compressed GH_2 storage, there is a tradeoff between weight and storage density that depends on the storage pressure. The upper figure shows GH_2 density at an ambient temperature of 15 °C (standardized equation from Lemmon et al. [81]). The lower figure shows the approximate trend in tank gravimetric efficiency with respect to storage pressure and mass of hydrogen stored. The absolute value for the gravimetric efficiency depends on the tank design and intended application.

Colozza's technique, but it is still simple enough to carry out by hand or quickly implement in a program. Safety factors for the design of these tanks vary depending on the application, but a factor of 2.25 is common [79,80].

Determining the optimal pressure for compressed GH_2 tanks is essential for achieving the best performance for a given application. Higher pressure enables higher energy density; 350 and 700 bar are common design pressures. However, higher pressure requires a heavier tank to withstand the pressure and incurs higher costs [79]. Fig. 4.4 shows the opposing influences of increased density and decreased gravimetric efficiency as pressure increases. It also shows increased gravimetric efficiency for greater volume but with diminishing returns. The gravimetric efficiency in this plot assumes a tank with a 3:1 length-to-diameter ratio and hemispherical end caps. The wall thickness sizing uses a simple netting analysis times an empirical factor to account for the liner, valves, regulators, and other components. For applications where high energy density is critical, higher pressures may be worth the increased cost, complexity, and weight. Nonetheless, there is variability in the chosen design pressure, even for similar applications. Universal Hydrogen has opted for a high 850 bar pressure for its composite tanks [69], while ZeroAvia has chosen 350 bar for its testbed aircraft [46] (this is subject to change for the production model).

Despite the downsides of compressed GH_2 storage, there is a compelling case for less weight-sensitive applications, such as small regional aircraft. Compressed GH_2 can be stored passively and at ambient temperature for long periods, enabling easier transportation and system design. It also avoids dealing with cryogenic fuel, simplifying onboard fuel systems and refueling operations. These factors may result in a lower cost for GH_2 storage than LH_2 for smaller aircraft.

4.2. Cryogenic liquid

Cryogenic LH_2 storage offers two main advantages over compressed gas storage: firstly, the density of the hydrogen is increased by a factor of 2 to 3; secondly, the hydrogen can be stored near ambient pressure—1 to 3 bar. These two advantages enable gravimetric efficiencies over 50%, shown in Fig. 4.2. The significant drawback is that hydrogen boils at 20 K, which requires significant insulation and careful fuel system design. Larger commercial transport aircraft are so weight-sensitive that higher gravimetric efficiencies are necessary to enable these missions to use hydrogen, as shown in Fig. 4.1. Airbus plans to use LH_2 for all future hydrogen aircraft in its ZEROe project [49]. Nearly all studies of hydrogen aircraft to replace current turbofan-powered commercial aircraft propose LH_2 storage [7,32,56].

Storing hydrogen at cryogenic temperatures brings new design challenges and increases complexity. The tank shape should have a low surface area-to-volume ratio to reduce heat entering the fuel. To further reduce boil-off, the tanks require thermal insulation. The tank structure needs to tolerate cryogenic temperatures. This means that the materials should maintain sufficient strength at low temperatures. In addition, when layering different materials, their thermal expansion coefficients should be compatible so that induced stresses during cooling and heating do not rupture the tank. The temperature of LH_2 is low enough to solidify nearly all gases and fluids, so special attention must be paid to avoid freezing other components and frost buildup inside and outside the aircraft.

Hydrogen that boils off rises to the gaseous upper region of the LH_2 tank, called the *ullage*. The ullage increases in pressure as hydrogen boils off, and it must be vented if the pressure reaches the tank's limit. Determining the appropriate amount of boil-off is a balance between reducing insulation weight and meeting all operational constraints. A commonly cited value to give an idea of the order of magnitude for an acceptable boil-off rate for hydrogen aircraft is 0.1% of the hydrogen weight per hour [64]. The short- to mid-range commercial transport aircraft concepts presented by Silberhorn et al. [82] boil off about 2% of the total fuel during the mission.

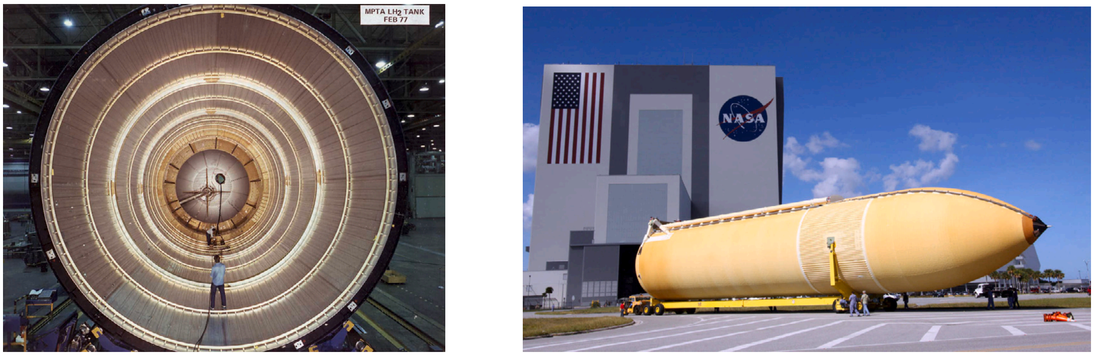
In practice, adequate boil-off is determined by operational constraints, such as sitting overnight without venting [64,83]. For a high-altitude long-endurance aircraft, Millis et al. [84] find that the most demanding time for the tank insulation is when the aircraft is parked with a full tank before takeoff in a hot desert, which can reach ambient temperatures 51 °C. In that scenario, the ambient environment is hot, and the ullage is small, so there is little room for the boil-off gas. Furthermore, the mass flow rate of fuel out of the tank is low or zero, so there is no pressure relief from an increasing ullage volume. Acceptable boil-off rates also depend on the mission length, aircraft size, tank venting pressure, and other factors.

4.2.1. Insulation

The most commonly considered insulation types are foam, sometimes referred to as *spray-on foam insulation* (SOFI), vacuum-based insulation, or a combination of the two. Active refrigeration has also been considered to avoid boil-off, but both Brewer [55] and Millis et al. [84] find that it adds complexity, and the added weight vastly exceeds the weight of fuel saved.

SOFI has a long history in space applications, including the Space Shuttle's external tank, shown in Fig. 4.5. However, it is poorly suited to hydrogen aircraft. The most significant barrier is its inability to handle repeated thermal cycles. To enable aircraft maintenance or storage, the tank must cycle between cryogenic operating conditions and ambient temperature without damage. SOFI is prone to cracking or delaminating from the tank's structural wall [85]. It may also require regular maintenance to ensure adequate thermal performance [64]. Therefore, it is practical only for single-use launch vehicles. Transport aircraft are expected to fly multiple times per day and operate for weeks or months between maintenance checks. Significant foam insulation technology breakthroughs would be required to meet these criteria.

Although SOFI has lifetime and maintainability issues, Brewer [55] and Verstraete et al. [87] still propose using it for transport aircraft LH_2 tanks, shown in Fig. 4.6. This is in part because they estimate it will enable higher tank gravimetric efficiencies. To work around SOFI's intolerance to thermal cycling, they suggest always leaving some LH_2 in the tank to keep it at cryogenic temperatures, except during major maintenance checks. The Boeing Phantom Eye aircraft is another



(a) Cross section of the Space Shuttle's external LH_2 tank showing the internal structure.

(b) The external tank was covered in a layer of spray-on foam insulation (the orange material) that was 1–2 inches thick [86].

Fig. 4.5. The Space Shuttle's external tank stored LH_2 and oxygen. Its outer layer was spray-on foam to insulate the cryogenic fuels (NASA images).

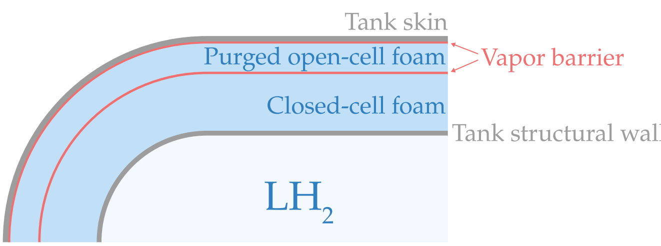


Fig. 4.6. A possible foam insulation configuration that uses an inner layer of closed-cell for its low thermal conductivity and an outer layer of open-cell foam that deforms as the inner layers grow and shrink from thermal expansion [55,87].

exception that used SOFI to insulate its LH_2 tanks [61,88]. At the time, SOFI was the only technology that met the mission requirements and had an acceptable technology readiness level. Less restrictive time and budget constraints would have enabled additional insulation technology development.

The heat leak of vacuum insulation is much lower than that of foam insulation. Vacuum-based insulation methods are also more reliable than foam-based systems. Airbus appears to have selected vacuum insulation for its LH_2 tanks [89]. In the tank's vacuum gap, radiation becomes a significant component of the heat leak. Placing multiple layers of highly reflective foil in the gap reduces the radiation. These layers, called *multi-layer insulation* (MLI), lower the thermal conductivity by two orders of magnitude compared to foam insulation [64, 90].

One drawback of vacuum-insulated tanks is that they require two walls to support the vacuum, resulting in heavy tanks. With current technology, gravimetric efficiencies of around 60% appear possible [84, 91]. There are several ways to reduce the weight of the vacuum walls. Machining a pattern of ribs into the wall to stiffen the structure is a promising technique [61,92]. Sullivan et al. [92] find that aluminum alloys are competitive materials for the tank walls but that a nanoclay-enhanced graphite-epoxy outer tank would be lighter. Employing composites creates new challenges, such as hydrogen permeation and mismatches in the thermal expansion coefficients of the fibers and matrix. If the application requires storing hydrogen for hours to days, vacuum-insulated LH_2 storage systems may be lighter overall than foam-insulated ones [64,92]. This is because the lower thermal conductivity of vacuum insulation results in less boil-off, which means less fuel must be loaded initially, and the tanks can be smaller.

A common concern with vacuum-insulated tanks is that the vacuum may fail, causing boil-off rates to increase dramatically [55,87]. This problem can be addressed by designing the venting system to handle such cases, as specified in CGA S–1.2 [93]. Upon failure, the boil-off rate is high. The tank's outer wall cools down drastically, causing the gases in the air to freeze on the tank's surface. This provides temporary insulation, reducing the boil-off rate. Additionally, it might make sense to include a thin layer of foam insulation to reduce the boil-off in the case of a vacuum failure [64,87].

4.2.2. Tank materials

An ideal tank wall structural material has a high strength-to-weight ratio, maintains strength at cryogenic temperatures, and has a low cost. Aluminum alloys, composite materials, stainless steel, and titanium alloys are frequent candidates [92,94]. Stainless steel is usually too heavy for aircraft and may experience hydrogen embrittlement under certain conditions. Titanium has suitable material properties but is one order of magnitude more expensive. Aluminum alloys and composites are the most commonly proposed materials for aircraft cryogenic hydrogen tanks. Aluminum has high strength, low susceptibility to hydrogen embrittlement, and low cost, making it suitable for cryogenic tank walls. Composites also have a promising future for further weight reduction. The current challenges are the higher cost compared to aluminum and complex failure modes [75]. Engineers also have limited experience with composites under these cryogenic conditions. Material challenges include cooling-induced stresses due to different thermal expansion coefficients in the resin and fiber, cracking, and potentially hydrogen permeability. The permeability could be addressed with a liner [95], but linerless designs may also be feasible [96,97]. Silberhorn et al. [82] and Brewer [55] use a safety factor of two to account for these unknowns, though that is likely conservative. Mital et al. [64] note mandated safety factors between 1.4 and 2. Considering all factors, aluminum alloys currently appear to be the best material, but further research and development may result in composites becoming advantageous for some applications.

4.2.3. Integral versus non-integral tanks

Another consideration when sizing the tank is deciding whether the tank's structure is integral to the aircraft structure or not. Fig. 4.7 shows sketches of integral and non-integral tanks. Integral tanks are commonly chosen in design studies because they enable aircraft weight savings [32,56,98,99], achieved by using the tank wall to serve multiple load-carrying purposes. In tube-and-wing configurations, the integral tank extends the fuselage with the same cross-sectional shape. Compared to non-integral tanks that must fit inside the fuselage structure, integral tanks can use the whole fuselage cross-section. This may allow shapes closer to a sphere with lower surface area-to-volume ratios because the tank can be shorter longitudinally.

Vacuum-insulated tanks have a thick outer wall, potentially making them well-suited to integral tank configurations. Foam-insulated tanks may be more challenging to make integral because their structural

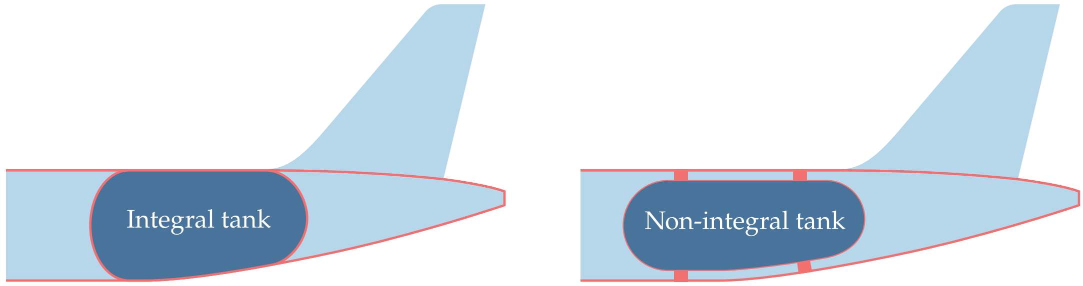


Fig. 4.7. The structure of an integral tank is integrated with the airframe and carries external structural loads, while the non-integral tank carries only fuel-related loads.

wall is usually underneath the foam insulation. Nonetheless, integral foam-insulated tank designs have been proposed [32,55].

The advantage of non-integral tanks is that they can be positioned anywhere in the aircraft. They are also easier to model because supporting aircraft structure loads need not be considered. Because detailed finite element models are not feasible in the conceptual design stage, the most common method of including aircraft structure loads to design integral tanks is to use a safety factor [57]. Onorato et al. [100] find that the larger the aircraft, the greater the advantage of integral tanks over non-integral ones because of the increased mass savings.

Expressing the gravimetric efficiency of integral and non-integral tanks introduces a bookkeeping challenge. Compared to the wall of a non-integral tank, an integral tank wall must be stronger to carry the additional airframe loads. The thicker wall could make integral tanks appear to have worse gravimetric efficiencies even though the aircraft weight is lower. A fairer tank gravimetric efficiency calculation should exclude the portions of the integral tank that contribute to the carrying of airframe loads. This should include at least part of the fuselage skin, but determining exactly how much to include requires detailed analysis.

4.2.4. *Tank shape*

A low tank surface area-to-volume ratio reduces the boil-off rate. The heat entering the LH_2 is proportional to the surface area of the storage tank. The boil-off rate is roughly proportional to the amount of heat entering the LH_2. The amount of hydrogen that can be stored is proportional to the tank volume. This has two consequences. The first is that the tank surface area should be reduced as much as possible for a given volume to reduce the boil-off rate (a sphere is best from a boil-off standpoint). The need to reduce the surface area-to-volume ratio is why it is not effective to store LH_2 in the wingbox as is done with kerosene. The second consequence is that larger tanks have an advantage from a boil-off perspective because surface area scales with the square of the characteristic dimension, whereas the volume scales with the dimension cubed. Fig. 4.8 illustrates these trends.

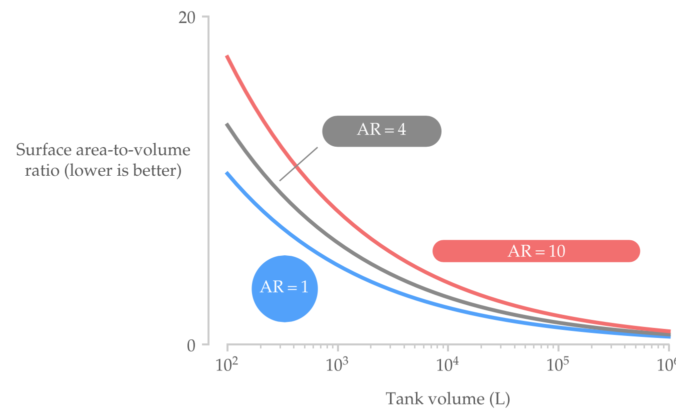


Fig. 4.8. The surface area-to-volume ratio decreases as the tank volume increases, which is desirable to reduce heat leak. Tank shapes closer to a sphere also reduce the surface area-to-volume ratio. AR is the length-to-diameter ratio.

LH_2 tanks must be able to contain pressures on the order of a few atmospheres. They are usually shaped to carry these loads efficiently, similarly to the GH_2 tanks discussed in Section 4.1. However, since the pressure is only a few atmospheres rather than the hundreds needed for GH_2, it might be feasible to design LH_2 tanks shaped to conform to the spaces available in the airframe. Conformal tank designs incur a weight penalty because they use a suboptimal pressure vessel shape. However, the weight penalty might be offset by improved aerodynamics or tank integration into the airframe.

NASA studied conformal tanks for single-stage-to-orbit (SSTO) vehicles. NASA's X-33 SSTO demonstrator, shown in Fig. 4.9, was one of the first concepts to use conformal LH_2 tanks [64]. The tanks were ahead of their time; they were integral to the airframe structure, constructed of fiber-reinforced composites, and linerless. Unfortunately, they failed during testing, and the project was eventually cancelled. NASA continued to pursue conformal and integral composite tanks, eventually succeeding by applying the lessons learned from the X-33 testing, such as using an impermeable liner [64,101]. Conformal tanks have garnered renewed interest; Collins Aerospace has proposed a variable geometry box-shaped LH_2 tank built with thermoplastic composites [102].

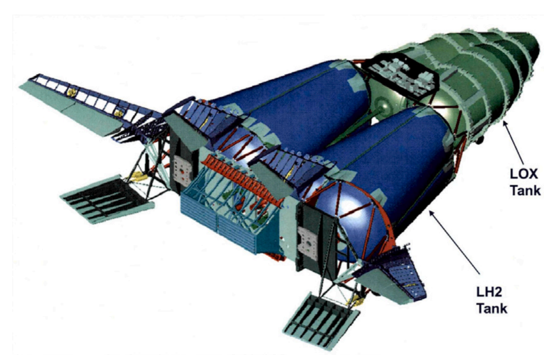


Fig. 4.9. The NASA X-33 project designed and tested conformal LH_2 tanks. *Source:* Reproduced from Letchworth [103].

4.2.5. *Operating pressure*

As with GH_2, the tank *design operating pressure*—also called *maximum expected operating pressure* (MEOP) or *venting pressure*—must be considered in the tank's structural sizing. These values are specified in absolute pressure rather than gauge because if the tank pressure reduced as the aircraft climbs to altitude, substantial amounts of hydrogen would boil off as the liquid and gaseous hydrogen in the tank equilibrate [55]. On this same front, the tank wall structure must be sized to contain the pressure differential between the design pressure and the minimum atmospheric pressure in which the aircraft flies. While lower design pressures result in lighter tank walls because of this structural sizing consideration, two factors require higher design pressures. The tank pressure must always be greater than the atmospheric (and cabin) pressure to prevent air from leaking in and forming a combustible mixture. Secondly, a higher venting pressure allows for more LH_2 to boil off before venting is necessary.

These two factors result in typical minimum operating pressures of about 1.2 bar and venting pressures between 1.5 and 3 bar. For example, Millis et al. [84] find that 2 bar is the optimum operating pressure for their high-altitude long-endurance aircraft's 8.5 ft diameter LH_2 tank. In their case, further reduction of the operating pressure offers no weight reduction because the tank's inner wall is already at its minimum manufacturable thickness. Smaller tanks tend to have a higher venting pressure because they need more insulation per unit of LH_2 due to the greater surface area-to-volume ratio. A higher venting pressure enables reduced insulation weight because more hydrogen can boil off before venting is necessary [87]. Conversely, larger tanks tend to have lower venting pressures. The tank is not filled beyond 95%–98% with liquid to avoid reaching the venting pressure too quickly when nearly full [84,87]. If the tank were filled beyond this level, the ullage volume would be so small that the pressure would rise too rapidly. The contraction of the tank when it is cooled from ambient to cryogenic temperatures must be considered when determining this fill level.

4.2.6. Modeling boil-off

Given the complex constraints on boil-off, the LH_2 boil-off must be modeled. The model can be divided into two necessary components. The first is a model of the heat entering the tank. The second is a model of how the heat leak affects the boil-off rate and pressure rise in the ullage.

To estimate the heat leak, Verstraete [57] develops a thermal circuit model. He assumes forced convection, radiation on the tank's surface, conduction through the tank walls, and natural convection in the tank interior. Verstraete et al. [87] adds a 30% empirical factor for heat transfer through support, connections, and piping.

Accurately estimating the boil-off rate and pressure rise in the ullage is challenging because of the complex coupled physics of heat transfer, phase changes, varying fluid properties with temperature and pressure, and thermal stratification and convection in the ullage and liquid. Mendez Ramos [104] reviews existing approaches and proposes a modified model for conceptual design. The simpler models traditionally used in conceptual design, namely the homogeneous model used by Verstraete [57] and Onorato [99], can be off by a factor of two [104]. Nonetheless, they may still offer insights in the conceptual design stage. By separating the tank into control volumes and incorporating empirical relationships, Estey et al. [105] and Mendez Ramos [104] (based on work by Ring [106]) develop moderate fidelity models that better capture the tank behavior while still maintaining complexity manageable in conceptual design.

4.3. Other storage methods

Alternative hydrogen storage methods include metal hydrides, chemically bound hydrogen, cryo-compressed hydrogen, and slush hydrogen. Overall, these other storage methods are too heavy to be useful for aircraft. Metal hydrides store 1 to 5% hydrogen by weight and require a long time to recharge [55]. Chemically bound hydrogen can store 5 to 15% hydrogen by weight but requires additional energy and complexity to separate the hydrogen [107]. Cryo-compressed hydrogen is pressurized LH_2 stored in a high-pressure cryogenic hydrogen tank (usually 100s of bars). As discussed in Section 4.2, higher venting pressures allow more boil-off before venting is needed (which may be needed with hydrogen cars that sit for extended periods) but require thicker tank walls that make the tanks heavy. Slush hydrogen, where a portion of the hydrogen is solid, has a slightly higher density and heat capacity than LH_2. Its downside is that it is energy intensive to produce because of how much cooling is necessary, which results in higher production costs (8%–17%) [56,57]. Brewer [55] identifies hypersonic aircraft as an exception where slush hydrogen may be beneficial.

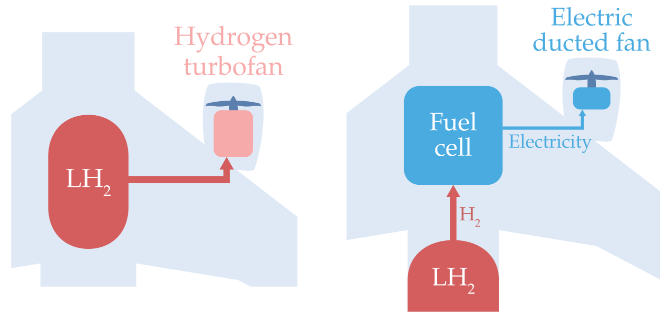


Fig. 5.1. The most commonly studied propulsion architectures are hydrogen combustion and pure fuel cell. As with electrified aircraft, there is a wide range of possible hybrid architectures [16].

5. Propulsion

Combustion in turbomachinery and hydrogen fuel cells are the two most common methods to turn hydrogen into thrust (see Fig. 5.1). Combusting hydrogen in a gas turbine to produce thrust leverages technology already used in commercial aircraft. Turbofans and turboprops are powered by gas turbines and cover the vast majority of current air transportation needs. Because hydrogen has different combustion properties than kerosene, new engines optimized specifically for hydrogen must be designed. However, it is possible to adapt existing turbomachinery to burn hydrogen by modifying the combustor and fuel supply system [108]. Fuel cells convert hydrogen to electricity, which can be used to power a propeller or ducted fan. Most of the thrust in modern turbofans is generated by the fan, so it is conceivable that a ducted fan can match the thrust of a turbofan. However, larger electric motors with high power density need to be developed. The highest power aerospace grade electric propulsion unit commercially available and flight tested is magniX's 650 kW magni650 [109]. Transport aircraft powered by electric ducted fans require rated powers of at least 1 to 10 MW [110]. Fuel cells produce electricity from hydrogen with efficiencies as high as 60% and only water vapor as a byproduct. The downside of fuel cells is that they are challenging to scale to high-power applications because of specific power and thermal constraints. While combustion solves fuel cells' specific power and thermal problems, it also has a higher environmental impact because it produces nitrogen oxides (NO_x) in addition to water vapor.

Fig. 5.2 shows the propulsion systems chosen by various concepts from industry and the literature. Fuel cells appear to be the dominant choice for small short-range aircraft, while hydrogen combustion dominates for large long-range aircraft. Fuel cells are preferred for smaller aircraft because, unlike turbomachinery, their efficiency is relatively constant across a wide range of sizes. This is because the electrical current a fuel cell can produce is approximately proportional to the active area available for the reactions to take place; doubling the active area roughly doubles the current [111]. Fuel cells' ability to scale down and maintain their efficiency can enable higher efficiency propulsion systems for these aircraft than is possible with hydrogen combustion. As the propulsion system power requirements increase, combustion eventually displaces fuel cells. This is because turbofans have higher specific power and fewer thermal management challenges than fuel cells; a fuel cell propulsion system for a 737-sized aircraft would be three times heavier than a similarly-sized turbofan system (see calculation details in Section 5.1). With creative engineering, the higher efficiencies of fuel cells may be beneficial for longer ranges because they can reduce fuel weight.

5.1. Combustion

Gas turbines have been the aircraft propulsion system of choice for decades in the form of turboprops and turbofans. Legacy manufacturers

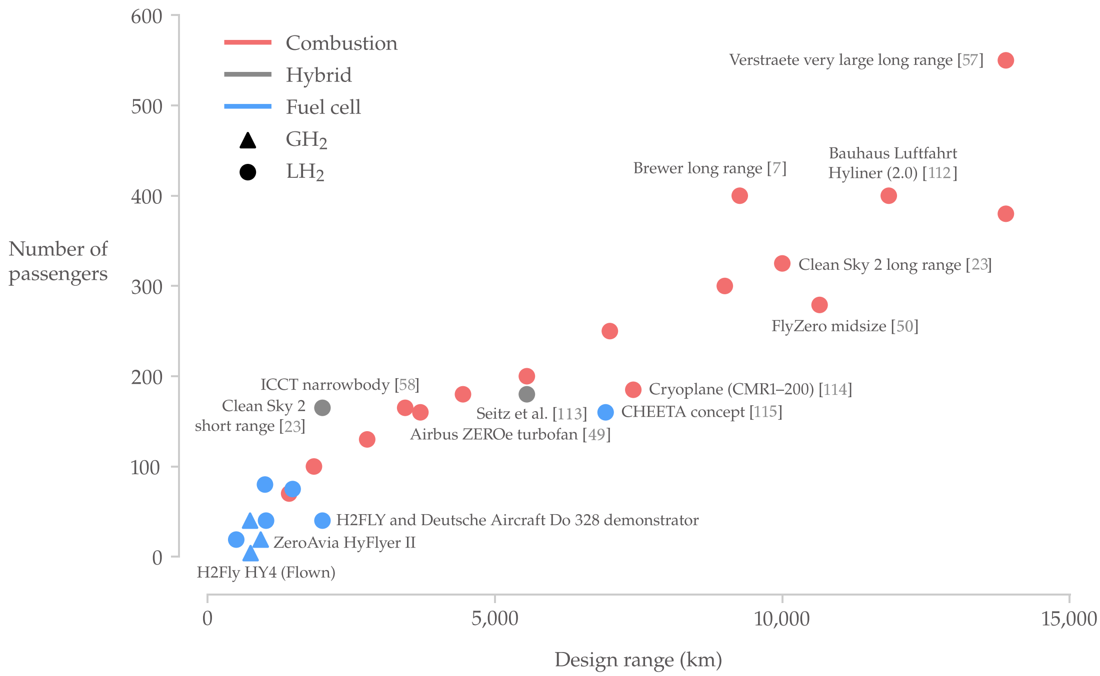


Fig. 5.2. Hydrogen combustion is currently the preferred propulsion system for aircraft larger than small turboprops (see Refs. [7,23,49,50,57,58,112–115]).

have accumulated vast experience in gas turbine propulsion thanks to sustained investment in the development of computational models, engineering knowledge, and manufacturing techniques. The concept of a hydrogen-powered gas turbine remains the same as kerosene-powered engines, and thus engineers can leverage the previous experience. Gas turbines have higher specific power than other propulsion methods, particularly for high-power propulsion. For example, the fuel cell-powered propulsion system of the 737–800-sized CHEETA aircraft [115,116] is roughly three times heavier[5] than estimates of the turbofan propulsion system installed on the 737–800 [117–119].

Because of the high specific power and historical engineering experience with turbomachinery, hydrogen combustion is the proposed solution for many hydrogen aircraft—particularly those from airframers and aircraft engine manufacturers. The four largest commercial aircraft engine manufacturers (GE Aerospace, Rolls-Royce, Pratt & Whitney, and Safran) have all published plans to build and test hydrogen combustion aircraft engines. CFM (a joint venture between GE Aerospace and Safran) is modifying a GE Passport turbofan to run on hydrogen. Airbus plans to fly the modified engine on an A380 demonstrator with liquid hydrogen tanks by around 2025 [120]. Pratt & Whitney announced its HySIITE project, funded by ARPA-E, to develop an LH_2 combustion engine with steam injection to reduce NO_x emissions [121]. They claim they will achieve greater thermal efficiency than fuel cells and lower operating costs than burning SAF. Rolls-Royce performed ground tests of an AE 2100 engine converted to combust hydrogen in 2022 and has plans to do the same with a Pearl 15 engine [122].

5.1.1. Combustor modifications

The fan, compressor, turbine, and nacelle in a hydrogen-powered gas turbine all work the same way as they do with kerosene and thus require minimal design changes, if any. The only component that requires significant changes is the combustor. To understand why hydrogen combustion is different, we must first review basic thermodynamic terms. The *stoichiometric fuel-to-air ratio* is the ratio of fuel mass flow to air mass flow where all the fuel is burned, and all the oxygen in the air is consumed. Hydrogen's stoichiometric fuel-to-air ratio is 1:34, which is less than half kerosene's 1:15. Dividing the actual fuel-to-air ratio by the stoichiometric fuel-to-air ratio yields the *equivalence ratio*, a helpful parameter for quantifying how much air is involved in the combustion. Equivalence ratios less than one correspond to lean combustion, in which more air is supplied than is necessary to fully burn the hydrogen. Hydrogen's wider flammability limits enable it to be burned much leaner than kerosene [123], as illustrated in Fig. 5.3.

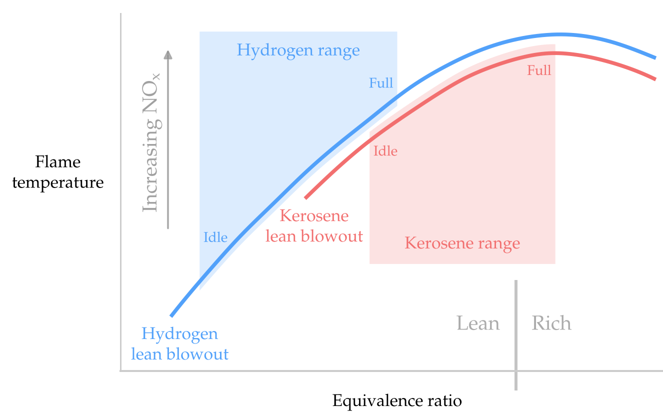


Fig. 5.3. Hydrogen has wider flammability limits than kerosene, which means that it can be burned leaner .
Source: Adapted from Brand et al. [108].

The downside of the greater flammability range is that the hydrogen-air mixture is so reactive that premixing before injection into the combustor is risky. Premixing introduces the risk of *flashback*, where the flames travel upstream from the combustor into the mixing zone.

Although hydrogen combustion does not produce soot, CO_2, or other pollutants produced by hydrocarbon combustion, it still produces nitrogen oxide (NO_x). The amount of NO_x produced depends on the residence time and combustion temperature. Hydrogen has a higher flame speed than kerosene. This means faster combustion and thus shorter residence times, yielding lower NO_x emissions and shorter combustors.

[5] The CHEETA propulsion system weight includes the fuel cell, ducted fan, and superconducting electric motor weights. The 737–800 installed engine weight incorporates nacelle, pylon, and auxiliary system weight estimates.

Hydrogen's flame temperature is greater than kerosene's when burned at an equivalence ratio of one. However, the flame temperature can be lowered because hydrogen can be burned much leaner than kerosene. Assuming the hydrogen-air mixture is fully mixed, the lower flame temperature of lean combustion reduces NO_x production. However, without sufficient mixing, hot spots form in regions where air and fuel are at stoichiometric conditions, producing NO_x. Mechanisms to increase the mixing intensity without premixing the fuel and air are necessary to enable low-NO_x hydrogen combustion.

Khandelwal et al. [123] cite lean direct injection (LDI) and micro-mix combustion as two mechanisms to mix hydrogen more thoroughly. Both use many small gaseous hydrogen injectors at an angle to the airflow direction to increase the turbulent mixing of the two streams. Marek et al. [124] performed experimental tests of LDI combustion and achieved low NO_x emissions, stable combustion, and no flashback even without significant optimization. Dahl and Suttrop [125] converted an Airbus A320 auxiliary power unit (APU) from kerosene to hydrogen with a micro-mix combustor. The initial conversion from kerosene to hydrogen gas nozzles with no further modifications resulted in minimal changes to the NO_x emissions. After fitting the micro-mix combustor, the NO_x emissions decreased by a factor of four.

5.1.2. Benefits of hydrogen over kerosene

Hydrogen's ability to combust at lean equivalence ratios reduces the temperature of the hot gas entering the turbine after combustion. Reduced turbine inlet temperature increases the turbine's lifetime and decreases the maintenance frequency. Corchero and Montañés [126] find a 37 K decrease in turbine inlet temperature for a hydrogen combustion engine compared to a similar kerosene engine, which translates to nearly doubling the turbine's life.

If the hydrogen is stored onboard as a liquid, it provides a large heat sink. This allows engine designers to explore creative ways of increasing performance. Boggia and Jackson [127] analyze three potential changes to a hydrogen-burning version of the A320's engine (IAE V2527-A5). They investigate precooling air entering the compressor to make compression easier and estimate a 5.7% reduction in thrust-specific fuel consumption (TSFC). They also consider cooling bleed air around the combustor and mixing it before the turbine, enabling increases to the turbine inlet temperature and a 2.1% reduction in TSFC. Finally, vaporizing the fuel is critical, but further preheating using the engine's hot exhaust reduces fuel consumption. Corchero and Montañés [126] estimate a 1%–3% decrease in TSFC by heating the hydrogen fuel from 25 to 250 K. Abedi et al. [128] also investigate uses for LH_2 in the engine cycle. They find only limited improvements to TSFC, but optimizing the engine cycle around these changes may uncover more significant fuel savings.

Other than the hydrogen-specific changes to the combustor and potential adjustments to the engine cycle that take advantage of the cryogenic fuel, most future advancements apply to both kerosene- and hydrogen-powered engines [129]. In particular, further increases in the bypass ratio to improve propulsive efficiency and increases in the overall pressure ratio to improve thermal efficiency. Advanced materials, design, and manufacturing will reduce engine weight.

5.1.3. Modeling for conceptual aircraft design

One essential metric in aircraft design is the thrust-specific fuel consumption (TSFC) of the engine, which is the fuel mass flow rate required per unit thrust the engine produces, that is

$$\mathrm{TSFC} = \frac{\dot{m}_{\mathrm{fuel}}}{F_{\mathrm{thrust}}}, \tag{2}$$

where $\dot{m}_{\mathrm{fuel}}$ is the fuel mass flow rate and F_{thrust} is the thrust. Although TSFC is widely used for comparing engines, it is not appropriate for comparing engines that use fuels with different energy densities. For example, a given mass flow rate of hydrogen delivers nearly three times more energy than the same mass flow of kerosene. Instead of quantifying the mass flow rate per unit thrust, it is more appropriate to quantify the *energy* consumption per unit thrust. This leads to the thrust-specific energy consumption (TSEC), which is written as

$$\mathrm{TSEC} = \frac{\dot{m}_{\mathrm{fuel}}\mathrm{LHV}}{F_{\mathrm{thrust}}} = \mathrm{TSFC} \times \mathrm{LHV}, \tag{3}$$

where LHV is the lower heating value of the fuel (120 MJ/kg for hydrogen and 43 MJ/kg for kerosene).

The TSEC for hydrogen engines is about the same as the TSEC for kerosene engines, though hydrogen's unique combustion and heat sink qualities may enable small improvements in TSEC. Maniaci [130] lists TSEC values from a range of papers that compare hydrogen and kerosene engines. The percentage change in TSEC at takeoff relative to kerosene ranges from −0.59% to −6.21%, with an average of −2.85%. At cruise, the average change in TSEC is −0.81%, with values ranging from −3.65% to +0.95%. Verstraete [57] assumes a TSEC savings of 3% for hydrogen, which he attributes to the increased water vapor in the combustor exhaust. Mukhopadhaya and Rutherford [58] hold TSEC constant between kerosene- and hydrogen-powered turboprop engines. Using the same TSEC is a reasonable conservative assumption for similar hydrogen and kerosene engine cycles.

Single-digit percent reductions in TSEC may be possible due to hydrogen's combustion properties [57,126]. There is a benefit from switching to hydrogen from kerosene due to increased water in the exhaust [57,127]. This water increases the exhaust's specific heat, which decreases the temperature and pressure changes across the turbine stages for a fixed power output (Boggia and Jackson [127] attribute this effect to a decrease in TSEC of 1.70% at takeoff and 2.76% in cruise). Further reductions in TSEC may be possible with modified engine cycles [128].

5.2. Fuel cells

A hydrogen fuel cell is a device that produces electricity from hydrogen and oxygen. Fuel cell propulsion architectures are usually proposed for small aircraft up to the size of a regional propeller aircraft (e.g., Dash 8 or ATR 72). Using a fuel cell avoids the costs and maintenance incurred by using turbomachinery. This is the architecture chosen by H2FLY's HY4 aircraft [131], Universal Hydrogen [48], and ZeroAvia [132]. Fuel cell propulsion architectures often use a battery to handle transient high-power requirements and rapid changes to throttle. Some architectures, including ZeroAvia's, supplement the fuel cell's power with batteries throughout the flight.

5.2.1. Fuel cell types

The most common fuel cell varieties considered for aircraft are polymer electrolyte membrane fuel cells (PEMFC), also known as proton exchange membrane, and solid-oxide fuel cells (SOFC) [133].

PEMFCs operate at low temperatures (30–100 °C [134]) and can start up and shut down in seconds. They also are the highest power density fuel cell type [111]. Careful humidification of the cell is critical to maintain adequate performance. A platinum catalyst is also required to speed up the chemical reaction (due to the low temperatures). PEMFCs have been a popular choice for transportation applications because of their portability and quick response times.

SOFCs operate at high temperatures (600–1000 °C [134]) and thus require some time to start up and shut down (at least 10 min and maybe an hour or more). One advantage of high-temperature operation is that the chemical reaction does not need a catalyst. Because the high temperatures enable the use of different materials, no humidification is necessary. SOFCs alone cannot surpass the power density of PEMFCs. However, if the high-temperature waste heat can be used productively (e.g., by generating power with a turbine or reforming hydrocarbon fuel), SOFCs may be a better choice.

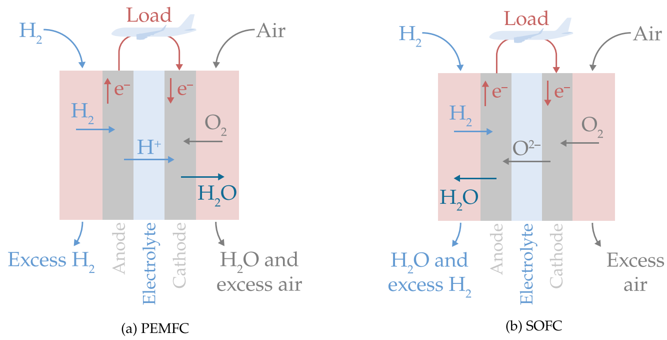


Fig. 5.4. In PEMFCs and SOFCs, hydrogen is consumed at the anode, and oxygen is consumed at the cathode, producing water.

5.2.2. *Fundamental principles*

Hydrogen fuel cells consume hydrogen at the negative electrode (anode), and oxygen at the positive electrode (cathode). The oxygen is usually drawn from the ambient air. Electrons from the hydrogen break off and flow through the circuit, powering the electric load. In a PEMFC, the positively-charged hydrogen ions flow through the electrolyte and meet up with oxygen and the electrons at the cathode, forming water. In an SOFC, the electrons meet the oxygen at the cathode, forming negatively-charged oxygen ions. These oxygen ions flow through the ceramic electrolyte back to the anode, where they meet with hydrogen ions and produce water. These two types of fuel cells are shown in Fig. 5.4.

Electrical current is directly proportional to the number of electrons flowing through the circuit. The faster the reaction in the fuel cell, the more current is produced. The reaction happens at the interface of the electrodes, electrolyte, and hydrogen or oxygen. A larger cell has more reaction sites and thus can produce more current. Therefore, it is common to normalize the current by the area of the cell, yielding the *current density*.

The electrical power produced is the product of the current and the voltage. The current is solely dependent on the reaction rate. The ideal voltage is dictated by thermodynamics—usually about 1 V per cell. The actual voltage is the ideal voltage minus three types of losses: activation losses, ohmic losses, and mass transport losses [111]. Each type of loss can be described as a function of current density. The curve of the actual voltage versus the current density is often called the *polarization curve* and is an essential tool for modeling fuel cell performance.

Activation losses, also called *activation overvoltage*, describe the voltage the chemical reaction uses to reduce the activation barrier. This voltage allows the chemical reaction to occur, but it reduces the fuel cell's usable voltage. In the high current density regime in which fuel cells usually operate, activation losses are described by the Tafel equation, $A \log\left(j/j_0\right)$, where A is a constant called the Tafel slope, j is the current density, and j_0 is the exchange current density [134]. The exchange current density j_0 represents the amount of electrons flowing between each cathode and the electrolyte at zero current density. In other words, it represents the amount of chemical activity at the electrodes when the fuel cell is not under load. A high j_0 is desirable because more activity generates more current. One way to reduce the activation overvoltage (and increase j_0) is to use catalysts. PEMFCs take this approach and use platinum as the catalyst. Another approach is to raise the operating temperature, which is how SOFCs work. A third is to make more reaction sites by using highly porous electrodes—all fuel cells do this. The Tafel equation suggests that activation losses approach negative infinity as current densities go to zero. This is not physical but can be avoided by modifying the Tafel equation to $A \log\left((j + j_n)/j_0\right)$, where j_n is the internal current density. Larminie and Dicks [134] give a typical value of 0.06 V for A, 0.04 mA/cm^2 for j_0, and 3 mA/cm^2 for j_n for a low-temperature cell.

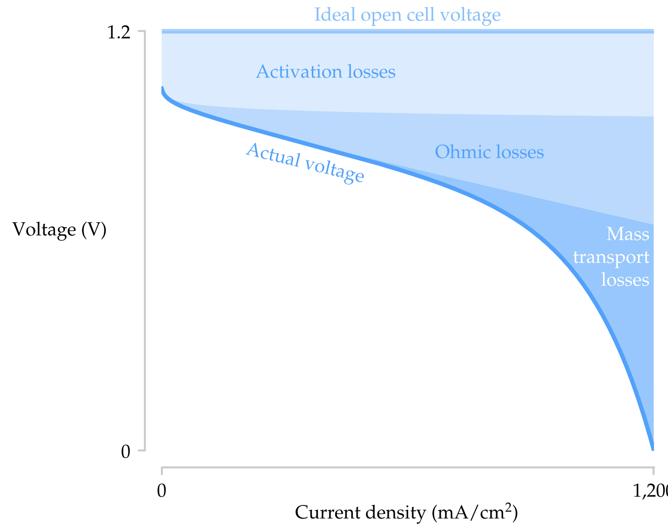


Fig. 5.5. Polarization curve for a fuel cell including the three sources of voltage loss. *Source:* Data from Laurencelle et al. [135].

Ohmic losses are a result of internal resistance in the fuel cell. These losses are called "ohmic" because they follow Ohm's law ($V = IR$). Therefore, the voltage reduction due to ohmic losses increases linearly with current, and thus also current density. While all fuel cell components contribute to these losses, the electrolyte is often the highest resistance part. The way to decrease electrolyte resistance is material-dependent, but generally, a thinner electrolyte has a lower resistance.

Mass transport losses, also called *concentration losses*, are caused by limitations on the rate at which reactants can reach the reaction sites. Depending on the fuel cell design, this limitation is dictated by the rate at which reactant gas can be pushed through the channels to the electrodes or the rate at which the reactants can diffuse through the electrodes to the reaction sites. This type of loss determines the cell's maximum current density because it describes the maximum rate at which the reactants can be supplied. The mass transport losses can be described by $c \ln\left(j_{\max}/(j_{\max} - j)\right)$, where c is a constant, $j_{\max}$ is the maximum current density, and j is the current density [111]. An alternative way of modeling the mass transport losses uses the empirical equation $m \exp(nj)$, where m and n are constants determined by fitting experimental data [136]. Unlike the first equation, the empirical equation has no theoretical foundation. However, it fits experimental data closely and thus takes into account effects that are not captured by the theoretical equation, such as the movement of water in the electrodes.

Fig. 5.5 shows the combination of the three types of losses to determine the actual voltage at a given current density. There are three regions in the resulting polarization curve. At low current densities, the activation losses dominate. At moderate current densities, the activation losses flatten out, and the ohmic losses determine the shape of the polarization curve. Mass transport losses grow rapidly at high current densities and set the maximum current density.

The power produced by a single fuel cell is not enough for most applications, so cells are stacked in series. To stack cells, current must be carried from the anode of one cell to the cathode of the neighboring cell. However, it is still necessary to deliver hydrogen and oxygen evenly to the surface of the electrodes. This is the function of the bipolar plates, which are made of a conductive material and designed with channels to carry the reactants to the electrodes. Fig. 5.6 shows an arrangement of fuel cells in series separated by bipolar plates. The bipolar plates must be designed to perform all these functions while being as lightweight as possible.

Cooling this stack is challenging. To appreciate how much heat must be removed, consider battery-powered electric aircraft. The thermal

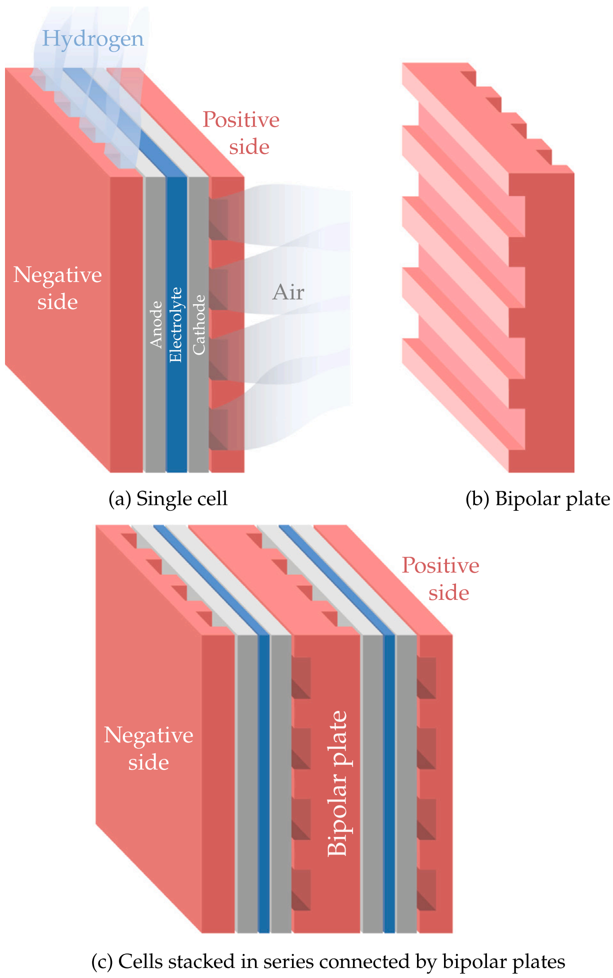


Fig. 5.6. To achieve enough power, individual fuel cells are arranged in series and separated by the bipolar plates. Many cells in series form the *stack*.

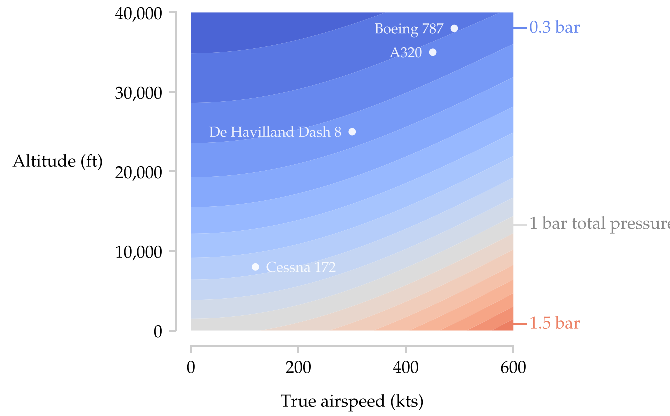


Fig. 5.7. Total pressure at a range of flight conditions in standard atmospheric conditions. Depending on the fuel cell's operating pressure, it may need substantial additional compression at higher altitudes.

management of electrical components for battery-powered aircraft is a known challenge [16]. This is because their temperature limits are relatively low, and the heat produced by electrical components accumulates in their structure instead of being expelled in the exhaust like in a gas turbine. Low-temperature PEMFCs have the same problem but must reject at least one order of magnitude more heat than electric components. This is because the efficiency of fuel cells is about 50%, which is much lower than a typical 95% efficiency of electrical components.

Wilberforce et al. [137] and Baroutaji et al. [138] discuss a range of cooling approaches and how they can be implemented. Air cooling, liquid cooling, and phase change cooling are the most common approaches. For applications requiring more than a few kilowatts, such as aircraft, liquid and phase change cooling are often the best or only options because passive and air cooling cannot reject enough heat. Kösters et al. [139] suggest using active cooling with a heat pump in combination with a phase change coolant to reduce the cooling system weight and drag for a low-temperature PEMFC. They find savings in net thrust of 16% compared to a liquid-cooled version. The most common approach to cool the fuel cell stack is by adding coolant channels to the bipolar plates. Because bipolar plates have so many functions, they often make up the majority of the stack's volume and weight, and they are the target of substantial design effort. Their shape is optimized to deliver reactants to the electrodes, manage cooling, and limit weight; their material must be highly conductive and lightweight.

Like turbocharging in combustion engines, the specific power of fuel cells can be increased by operating at higher pressure. The power increase is due to a reduction in the cathode activation overvoltage. The voltage increase is proportional to the logarithm of the pressure rise [134] (new operating pressure divided by original operating pressure, usually atmospheric). In other words, increasing operating pressure helps somewhat but eventually yields diminishing returns. Unlike turbocharged internal combustion engines, PEMFCs do not produce hot exhaust gas that can drive a compressor. Using a turbine to recover pressure from the PEMFC exhaust can still be worthwhile, but the recovered power alone cannot drive the compressor. Compressors for fuel cells must be powered by electricity produced by the fuel cell itself. The question now becomes whether the increase in the fuel cell's power is worth the power used by the compressor, the added weight, and the increased complexity. The answer depends on the fuel cell and the application. Schröder et al. [140] design a fuel cell to supply more than 300 kW of auxiliary power for a commercial aircraft and find that pressurizing the fuel cell to between 1.5 and 2.0 bar absolute pressure achieves the optimum overall system efficiency. Larminie and Dicks [134] provide a quantitative method to determine if incorporating a compressor may be worthwhile. For aircraft, the operating pressure is further complicated by the variation in total pressure at different altitudes and speeds (Fig. 5.7 shows total pressure at a range of flight conditions). Particularly for larger aircraft that operate in conditions with lower total pressure, fuel cell pressurization is likely beneficial or even necessary to improve fuel cells' specific power.

5.2.3. PEMFC operation

PEMFCs require humidification and water management. The electrolyte membrane is often made of Nafion, a polymer material that looks like plastic wrap and must be kept wet to conduct the positively-charged hydrogen ions efficiently. On the other hand, the electrodes must not become flooded by water, which clogs their carefully-crafted, porous structure.

This is further complicated by the reactions and forces that create and move water around the cell, illustrated in Fig. 5.8. In PEMFCs, water is created at the cathode. Water is also pushed from the anode toward the cathode (the wrong direction to hydrate the membrane) by electro-osmotic drag, a force created by the hydrogen ions moving across the electrolyte membrane. A handful of other forces, including diffusion, push water in the opposite direction [141].

The final complicating factor is that as the air moves across the cathode, it absorbs water and heat. If it absorbs a lot of water and little heat, the relative humidity may be nearly 100% by the time the air reaches the exit. If it absorbs much heat and not much water, the relative humidity may decrease substantially by the exit. Both extremes are undesirable because they result in too little or too much water being removed from the downstream portion of the cathode.

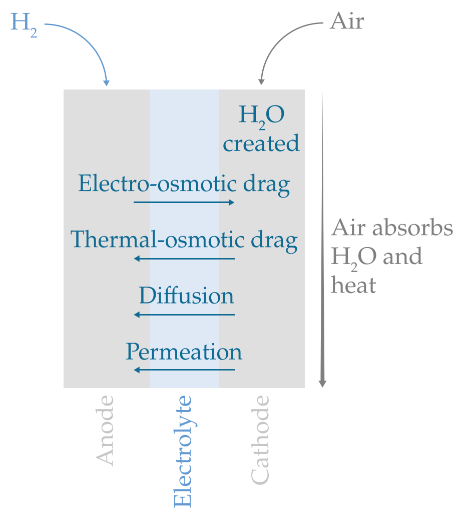


Fig. 5.8. Careful water management in PEMFCs is necessary to keep the electrolyte membrane hydrated without flooding the porous electrodes.

Fig. 5.9. The fuel cell's balance of the plant can be as heavy and large as the fuel cell stack itself. The fuel cell propulsion unit for H2FLY's HY4 aircraft includes a thermal management system, power conditioning, water management, and more (H2FLY GmbH image).

These effects can be controlled by adjusting the temperature and humidity of the gases being sent to the fuel cell stack. The amount of air flowing into the stack can also be changed. In practice, more air is blown through the stack than is necessary for the chemical reaction—partially for water management and potentially for thermal management. The fuel cell's designer also controls the operating pressure, which changes the amount of water required to achieve a given relative humidity.

As the fuel cell operates, nitrogen (from the air) and water travel to the anode. The build-up of nitrogen and water degrades the fuel cell performance [142]. Continued operation without clearing the nitrogen and water can permanently damage the fuel cell. Periodic purging of the anode compartment is essential to maintain the fuel cell's performance and lifetime. Unfortunately, purging wastes hydrogen. Thus, the selected purge time interval is a compromise between maintaining the fuel cell's performance by purging the impurities and avoiding hydrogen loss. A reasonable time interval between purges is in the order of minutes [143].

Small amounts of carbon monoxide exist in hydrogen produced from fossil fuels. This carbon monoxide can poison low-temperature PEMFCs [144]. Even very low amounts of carbon monoxide in the order of 10 ppm can permanently absorb onto the surface of the platinum catalyst, preventing the chemical reactions from occurring. To prevent this, the hydrogen fuel should have low carbon monoxide levels.

5.2.4. SOFC operation

Solid oxide fuel cells operate at high temperatures of 600–1000 °C, which provides several benefits. The reaction occurs more readily at higher temperatures, which means that no precious metal catalyst is necessary. A greater temperature difference between the fuel cell and ambient air eases thermal management. Oxygen ions can be used as a charge carrier with a ceramic electrolyte, which requires no water management. Finally, the high-temperature waste heat can be useful. One commonly cited use for the waste heat is to reform fuel (either internally in the cell or externally), which in this case means converting hydrocarbon fuel to hydrogen (to be used by the fuel cell) and other products [111]. However, this does not apply when pure hydrogen is already stored onboard. Another use is with hybrid fuel cell and hydrogen-powered gas turbine propulsion architectures, where the fuel cell's heat preheats the air entering the combustor [145].

The high temperatures also introduce new challenges. SOFCs have long startup times and limited shutdowns in their lifetime [146]. Larger temperature changes on startup and shutdown introduce material and mechanical difficulties, including thermal expansion compatibility and sealing [111]. Additionally, the air and fuel must be preheated.

The materials and components required for SOFCs produce lower specific power than PEMFCs, but similar efficiencies. If the waste heat can be used effectively for fuel reforming or preheating air in a gas turbine hybrid architecture, SOFCs may be worthwhile; many SOFC and gas turbine hybrid architectures have been proposed [147]. Otherwise, PEMFCs are usually chosen because of their high specific power and quick startup.

5.2.5. Balance of plant

As previously explained, fuel cell stack operation might require thermal management, pressurization, and humidification. Other processes might be required, such as electric power conditioning. Similarly to the tank auxiliary systems in Section 4.1, the components required to support the fuel cell's operation form the *balance of plant*. The balance of plant must be included when modeling the fuel cell system's mass, volume, pressure loss, and cost. In practice, the balance of plant can weigh at least as much as the fuel cell stack, if not more. Visually, the balance of plant often obscures the fuel cell, as shown in Fig. 5.9.

5.2.6. Aircraft design considerations

An important distinction exists between a fuel cell's efficiency and power output. We define efficiency as the ratio of the electrical power produced by the stack to the rate at which energy (in the form of hydrogen) flows into the stack. In practice, the overall system efficiency may include other factors, such as the electricity supplied to the balance of plant's compression system. Nonetheless, the stack efficiency still gives a sense of the overall trends.

For intuition on stack efficiency, let us consider voltage and current. Electrical power (the numerator in the stack efficiency equation) is the product of the current and voltage. Current is directly proportional to the amount of fuel entering the stack because the reactant gases supply the electrons flowing through the circuit. This leaves voltage to determine the shape of the efficiency curve, so it should not be surprising that the efficiency is similar to the polarization curve.

As shown in Fig. 5.10, the efficiency decreases as the current density increases. On the other hand, the power (and specific power) increases as current density increases. These opposing effects introduce an interesting problem for aircraft designers [148]. Oversizing the fuel cell to operate at low current density reduces the necessary fuel weight because the fuel is used more efficiently [140,149]. However, this results in a larger, heavier, and more expensive fuel cell. Alternatively, sizing the fuel cell to operate at maximum specific power reduces the

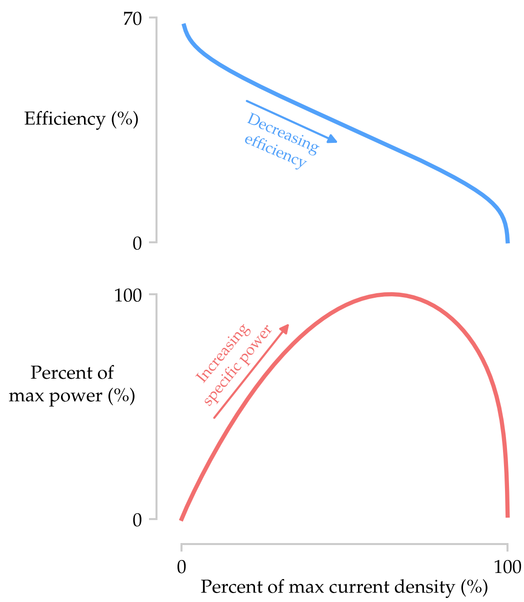


Fig. 5.10. Fuel cells are most efficient at low current densities but have the highest specific power at higher current densities. Designers must decide how to size the fuel cell to best balance the weight of the needed fuel and the weight of the fuel cell while meeting maximum thrust requirements.

fuel cell weight but increases the fuel required. The optimal balance between the fuel and fuel cell's volume, weight, and cost depends on the particular aircraft.

Unlike a gas turbine's power output, the power produced by a fuel cell is insensitive to altitude, assuming a compressor is used to maintain the absolute pressure of air flowing into the stack as altitude changes. However, the compressor requires more power as altitude increases and total pressure drops, which adds some altitude sensitivity. The thrust of a gas turbine engine decreases substantially with altitude, so top of climb is a common design point.[6] The reduced altitude sensitivity of fuel cells may impact the design points [149]. If the takeoff design point is what constrains the fuel cell power, there may be substantial extra power available at altitude compared to what a gas turbine would provide. This could be a benefit because the fuel cell could operate in the higher efficiency portion of its polarization curve. However, if the fuel cell is sized for top of climb, less power may be available at takeoff than a gas turbine would provide.

For fuel cell thermal management system design, knowing how the fuel cell's efficiency is measured is vital. The efficiency can be measured relative to hydrogen's lower heating value (LHV) or higher heating value (HHV). The LHV corresponds to the heat produced when hydrogen is combusted. The HHV is the LHV plus the heat generated when the water vapor from the combustion is condensed. This becomes relevant for fuel cells when the water vapor exhaust is manipulated. In some cases, the thermal management system rejects more heat than predicted by the LHV efficiency because additional energy can be extracted by condensing the exhausted water vapor.

Aircraft propulsion systems must respond to rapid throttle changes and achieve high thrust for brief periods. PEMFCs appear to have fast enough response times to serve this purpose [150]. However, a battery is often included to serve as a buffer and to enable higher transient peak power output [72,151,152]. With careful system design, it may be possible to remove the battery.

[6] *Top of climb* is the point where transport aircraft transition from climb to cruise. This point often sizes turbofan engines because their thrust decreases with altitude, and the aircraft is still heavy with fuel at this point.

Finally, there is a sentiment within the aircraft design community that fuel cells are suitable only for smaller aircraft. Most current hydrogen fuel cell concepts are for regional aircraft or smaller because of the fuel cells' low specific power and power density compared to conventional gas turbines. There is also a more significant thermal management challenge as the power requirements increase. White et al. [116] find that the thermal management system drag could be up to 10% of the total aircraft drag for their 737-sized concept. Thermal management has coupled effects on the aircraft and propulsion system design, so it should be considered early in the design process. Despite the challenges, it may be possible for fuel cells to achieve better performance than gas turbines, even for long-range aircraft, by taking advantage of fuel cells' high efficiency to reduce fuel weight. Research is underway on novel fuel cell concepts to replace current narrowbody aircraft [153] and to address the thermal management issues [116].

5.2.7. Recent developments

The growing interest in hydrogen as a solution for hard-to-decarbonize transportation sectors has spurred significant advancement in fuel cells, particularly PEMFCs. Bhatti et al. [154] give an estimate of technology parameters and costs of PEMFCs through 2050. The most commonly stated challenges of fuel cells are the high cost and low durability [141,155–157]. The cost of fuel cells is expected to decrease as mass production scales up. Researchers are developing cheaper and higher-performance membrane materials [141]. Bipolar plate material, durability, and channel geometry research is ongoing.

Toyota has invested in hydrogen technology for vehicles since the 1990s and is ramping up its efforts. For the Mirai fuel cell vehicle, Toyota developed a self-humidifying PEMFC to reduce weight and volume. The self-humidifying system supplies the reactant gases to the electrodes in opposite directions to promote internal water circulation and diffusion through the electrolyte. Additionally, they have developed new bipolar plate geometries to improve the flow of gases through the cell. These improvements, in combination with other optimizations, have allowed them to more than double their stack's power density and specific power to 3.1 kW/L and 2.0 kW/kg, respectively, and increase current density by a factor of 2.4 [158].

Another advancement poised to decrease the weight and size of PEMFCs is transitioning to high-temperature PEMFCs (HT-PEMFC) [159]. The thermal management system is a significant contributor to the size and weight of a PEMFC's balance of plant [155], so reducing its weight is critical to increasing specific power. Operating at higher temperatures simplifies the thermal management challenges by providing a larger temperature difference between the fuel cell and ambient air. Another benefit of HT-PEMFCs is that they are less sensitive to carbon monoxide poisoning. HT-PEMFCs' near-term challenge is the high weight of their fuel cell stack, but that is expected to improve with continued material and design research [154].

HyPoint Inc [160], owned by ZeroAvia, is developing an HT-PEMFC that operates in the 140–180 °C range. The higher operating temperature allows them to cool the fuel cell with air instead of liquid and use the same compressed air to feed the stack. Phosphoric acid is used instead of water in their electrolyte, which circumvents the need for water management. They claim that these advancements enable a 61% weight reduction, resulting in a specific power of 2 kW/kg including the balance of plant. They also quote a carbon monoxide tolerance in the order of a few percent, which is substantially higher than current low-temperature PEMFCs.

A handful of hydrogen fuel cell regional aircraft demonstrators are expected to fly in the coming years. H2FLY and Deutsche Aircraft are converting a Dornier 328 to a 40-seat hydrogen fuel cell propeller plane with a 1.5 MW hydrogen system set to fly in 2025 [161]. ZeroAvia is retrofitting a Do228 for certification in 2024 [162], with interest from Alaska Air [163] and United Airlines [164]. Universal Hydrogen is retrofitting existing turboprops with hydrogen-powered fuel cells and already has orders from airlines [165]. They aim to fly paying passengers by 2025. The German Aerospace Center (DLR) is developing 1.5 MW fuel cell systems for regional transport as well [166].

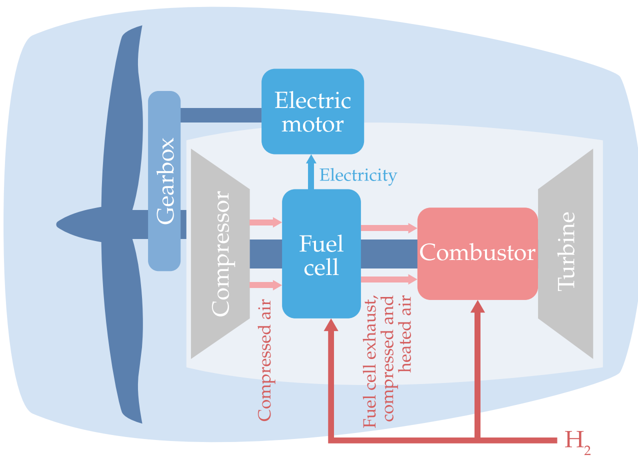


Fig. 5.11. A highly-integrated fuel cell and combustion hybrid propulsion architecture proposed by Bradley and Droney [168].

5.3. Hybrid

Hydrogen propulsion offers the same hybridization opportunities as battery-powered hybrid aircraft [16]. Adding a fuel cell enables more tightly-integrated hybrid architectures. Bradley [167] describes a range of possible architectures combining batteries, fuel cells, and gas turbines. A particularly novel architecture integrates a fuel cell with a hydrogen gas turbine, as shown in Fig. 5.11. The gas turbine's compressor pressurizes air used by the fuel cell, and the fuel cell's hot product gases are fed to the gas turbine's combustor, increasing thermal efficiency. This architecture was studied in the Subsonic Ultra Green Aircraft Research (SUGAR) program [168].

Waddington et al. [149] investigate a similar architecture with an SOFC system and small turbogenerator that combusts the remaining hydrogen exiting the fuel cell. They find that the low technology readiness level of SOFC systems relative to PEM fuel cells adds uncertainty to the specific power and performance of the solid oxide fuel cell. Their project targets zero NO_x emissions, which leads them to rule out SOFCs because the high temperatures produce NO_x. However, they mention that future SOFC systems may become a compelling technology for reducing aircraft energy costs.

Seitz et al. [113] explore another variation of the SOFC and gas turbine hybrid architecture that collects water vapor from the fuel cell exhaust and injects it into the gas turbine to improve efficiency and decrease NO_x emissions. Their system separates the fuel cell and gas turbine, so the fuel cell is not integrated into the gas turbine's engine cycle. The concepts by Bradley and Droney [168] and Waddington et al. [149] likely add water vapor to the combustor to some extent (unless they explicitly extract it) because there is water in the SOFC exhaust. However, Seitz et al. [113] focus specifically on the relationship between the amount of water vapor injected and the gas turbine's efficiency by varying the SOFC and gas turbine power split. They find a 7.1% decrease in block fuel burn and 62% decrease in NO_x compared to their turbofan-powered baseline aircraft.

It has also been proposed to replace the auxiliary power unit (APU) with a fuel cell. The Cryoplane project [56] mentions the option of using a fuel cell for the APU, which can provide electrical power in flight—it may be possible to power it with the boil-off gas from the LH_2 tank, reducing the amount of fuel that must be vented. This could replace the need for electricity generation and hot bleed air from the gas turbine, allowing it to be downsized. Burger [169] investigates using a fuel cell as both an APU and additional tail propulsor.

Lastly, DLR is exploring a range of novel hybrid architectures [170]. One concept uses fuel cells for cruise and taxiing with gas turbines for takeoff and go-around conditions.

5.4. Additional considerations

Storing hydrogen as a liquid adds complexity to the fuel system, but it also offers possible synergies because the cryogenic fuel can be used as a heat sink. One idea for an electric propulsion architecture is to use the cryogenic fuel to cool electrical components, which could reduce drag from radiators in the thermal management system. Taking this idea further, the LH_2 could be used to cool electrical components to the point that they are superconducting. The CHEETA program takes this approach, using the LH_2 to cool superconducting electric motors, inverters, and transmission lines [115]. Airbus UpNext's ASCEND demonstrator program also aims to investigate superconducting electrical propulsion systems with LH_2 [171]. Harnessing superconductivity would increase efficiency, system-level specific power, and power density of the electrical components.

6. Fuel system

Ultimately, both fuel cells and gas turbines consume gaseous hydrogen. If the fuel is stored as a cryogenic liquid, it must be converted from liquid to gas at some point. The point where the fuel is vaporized affects the design of the entire fuel system because it determines whether the fuel is moved within the aircraft as a gas or cryogenic liquid. Most concepts in the literature store the fuel as LH_2 and burn it in a gas turbine (see Fig. 5.2). These designs use an LH_2 fuel system and vaporize the fuel using heat generated by the gas turbine before it is combusted [9,129]. For fuel cells, a separate heat exchanger can be used to vaporize the fuel—this could use heat from a high-temperature fuel cell, such as an SOFC [84].

If the hydrogen is stored as a pressurized gas, the cryogenic challenges do not apply. Small uncrewed fuel cell aircraft that store hydrogen as LH_2 often also use a GH_2 fuel system that takes fuel from the tank's ullage [172,173]. A resistive heater in the LH_2 tank generates more GH_2 when the natural boil-off alone is insufficient.

Cryogenic liquid fuel systems are usually preferred over pressurized gaseous ones because of tank ullage pressure constraints [84]. During cruise, the natural boil-off will almost certainly be less than the fuel mass flow rate required by the engines. Therefore, if the engines were fed ullage gas, the ullage pressure would plummet. Because the density of LH_2 is far greater than the density of the GH_2 in the ullage, feeding the fuel system with the liquid results in a slower ullage pressure decrease for a given fuel mass flow rate. However, there may be configurations where pressurizing the ullage and using it to feed a gaseous fuel system makes more sense.

Whether the fuel system is liquid or gaseous, cryogenic fuel tanks require heaters to prevent the ullage pressure from reducing too much. When liquid is removed from the tank, the ullage volume increases. When ullage gas is drawn from the tank, the amount of GH_2 in the ullage decreases while the ullage volume remains the same. In both cases, the boil-off caused by the tank's heat leak may not be sufficient to maintain the ullage pressure. Additional boil-off can be generated by adding heat to the tank.

Cryogenic liquid fuel systems must minimize the amount of boil-off in the fuel lines because liquid fuel systems can only handle so much vapor in the liquid [9]. These systems use insulated fuel lines to limit the heat entering the system. Fuel lines are usually vacuum-jacketed or foam-insulated [55]. Every component in an LH_2 fuel system must be carefully designed to minimize the heat leak into the cryogenic fuel.

Because hydrogen has a wide flammability range and is prone to leaking due to its small molecular size, it is vital to incorporate leak detection into the fuel system [174]. Aircraft-specific hydrogen leak detection must be developed for future hydrogen aircraft [175].

Once the LH_2 reaches the engine or fuel cell, it must be vaporized and likely heated. Both fuel cell and gas turbine aircraft have components that need cooling, such as the fuel cell stack, engine oil, turbine blades, or compressed cabin air. There is an opportunity to take

Fig. 7.1. Proposed tube-and-wing configurations store the hydrogen in the fuselage. The darker area of the fuselage shows the passenger cabin.

advantage of this relationship by designing a symbiotic system that reduces the thermal management system's drag compared to a design where the two systems are separate [129].

More technology development is necessary to enable these cryogenic fuel systems. The most cited challenge is the lack of cryogenic pumps suitable for aircraft [9,23,129,153,175]. The rocket industry has already addressed this challenge. However, cryogenic rocket pumps have different requirements: they have much shorter operating times (a few minutes for launch), shorter expected lifetimes, and higher flow rates. Aircraft applications demand pumps that can operate reliably for hours, have a lifetime of thousands or tens of thousands of hours, and handle the lower mass flow rates required by aircraft. Other cryogenic fuel system technologies also require further development, including valves, vents, seals, bearings, and methods for accurately controlling gaseous fuel lines.

7. Aircraft configuration

Hydrogen aircraft configurations differ from conventional aircraft designs because of the hydrogen storage requirements. Whether stored as a liquid or gas, hydrogen takes up at least four times more volume than kerosene for a given amount of energy. For LH_2 storage, reducing the heat leak favors tank shapes with low surface area-to-volume ratios. Because of hydrogen's low volumetric energy density, limiting the weight and drag penalties of integrating hydrogen tanks into an aircraft configuration is vital.

Because wings have a high surface area-to-volume ratio, the tanks are usually placed elsewhere, and the wing is "dry". (One exception is Silverstein and Hall [5], who wanted to store the maximum possible amount of fuel to maximize range.) A dry wing no longer benefits from load alleviation due to fuel weight, probably resulting in a heavier design. Detailed aerostructural design considering all relevant load conditions and dynamic aeroelasticity would be necessary to design a dry wing with optimal trades between weight and drag.

For GH_2 storage, long and thin pressure vessels that fit in large wings may be feasible. However, GH_2 is proposed mainly for smaller aircraft (see Fig. 5.2), which have wings that may be too thin for wing-based storage to be effective. Lastly, current aircraft wings do not have the volume necessary to store enough hydrogen for long commercial flights [176].

7.1. Tube-and-wing

The most commonly proposed configurations involve integrating the tanks into the fuselage of a conventional tube-and-wing configuration. Fig. 7.1 shows a few examples of such configurations. Some configurations reserve the whole cross section in a portion of the fuselage for one or more tanks [7,32,49,50,112]. This approach offers the highest tank volume to surface area ratio because the tanks use the entire fuselage width. It also enables integral tank designs because the tank's outer surface conforms to the fuselage's outer surface.

For aircraft with a low fuel fraction (smaller aircraft with shorter range), it may be possible to employ this configuration with only a single fuselage tank behind the rear pressure bulkhead [56]. Trim and stability constraints force larger aircraft with this configuration to have both fore and aft tanks to limit the center-of-gravity movement. The forward tank is placed between the cabin and the cockpit. It is unclear whether regulations require pilot access to the cabin, so a cutout in the forward tank may be necessary [57]. This configuration may not be suitable for narrowbody aircraft if access is required because their fuselage diameter is not large enough for a viable cutout [56].

Another possible tube-and-wing configuration places the LH_2 tank above the fuselage along its length [177]. Because the tanks are longer and thinner, they require more insulation for a given amount of fuel. Furthermore, their walls cannot double as fuselage structure to make integral tanks. These factors incur a weight penalty, which results in degraded performance compared to the whole cross-section tank configuration. Troeltsch et al. [112] perform a trade study that compares the fuel consumption of a configuration that stores fuel in large tanks fore and aft of the cabin in the whole cross-section to one that stores fuel above the cabin, and also a combination of the two. The configuration with tanks at the front and rear of the cabin that fill the fuselage's cross-section has over 10% lower fuel burn.

While the over-cabin configuration has a performance penalty, it offers several safety benefits [176]. Placing tanks higher protects them from debris on landing and takeoff that could puncture the tank. They are also safer if a belly landing is necessary (e.g., if the landing gear fails to extend). Finally, positioning the tanks above the cabin and outside the pressure vessel increases the probability that leaks vent upward and away from the passenger cabin.

7.2. Unconventional configurations

Because hydrogen's onboard storage requirements differ significantly from kerosene's, the tube-and-wing configurations that are well suited to current kerosene aircraft may not be the best choice for hydrogen aircraft. The blended wing body (BWB) configuration [178–180], shown in Fig. 7.2, is the most promising among the unconventional designs, particularly for long-range missions [177,181]. The blending region between the cabin and the wings creates a large irregularly-shaped volume. Loading and storing cargo in this volume is impractical because of its shape. However, this volume may be convenient for storing hydrogen with a low drag penalty.

However, there are still questions about the BWB's viability. Designing a lightweight structure that can withstand cabin pressure loads is one of the most significant challenges. The PRSEUS project aimed to address this challenge with novel composite manufacturing techniques [182–184].

Other unconventional configurations that have been proposed include twin fuselages and podded wing tanks. However, these configurations tend to have inferior overall performance because of the increased drag [56,177].

8. Cost

Operating cost is a significant driver for the commercial aviation industry. Hydrogen aircraft change the cost in two ways: aircraft cost, including acquisition and maintenance, and fuel cost. Both categories are subject to high uncertainties. Accordingly, operating cost estimates compared to similar kerosene aircraft range from a slight decrease [55] to a 50% increase [23] or more, depending on the aircraft size, propulsion system, and technology assumptions.

Hydrogen aircraft acquisition cost will be higher than conventional aircraft because of the hydrogen storage tank and system integration. In addition, the first hydrogen aircraft must be priced to offset the higher research and development costs involved. Hoelzen et al. [185]

Fig. 7.2. Two potential arrangements for hydrogen tanks in a BWB configuration. The darker area shows the passenger cabin.

estimate a 12%–13% increase in the acquisition cost component of direct operating cost for short- and medium-range aircraft. Depending on their price, fuel cells may also increase the acquisition cost if used in the propulsion system.

The change in maintenance cost is also uncertain. There has been speculation that hydrogen turbomachinery has a longer life and requires less maintenance than their kerosene-powered counterparts because hydrogen burns more cleanly—Janić [186] and Brewer et al. [9] estimate a 25% longer engine life. On the other hand, maintenance costs could increase due to the complexity of operating and maintaining LH_2 tanks and fuel systems. Like all primary structures, the LH_2 tanks require regular inspection to ensure the insulation and structure are in adequate condition [187]. Safely defueling and purging the tanks for maintenance is an involved process [188,189].

The other significant influence on operating cost is the fuel, both in terms of how efficiently the aircraft uses the fuel and the fuel's unit cost. The change in fuel energy required compared to kerosene aircraft depends strongly on the tank gravimetric efficiency, as previously explained (see Fig. 4.1). Mukhopadhaya and Rutherford [58] estimate an energy usage increase of about 10% for hydrogen combustion turboprop and narrowbody aircraft with tank gravimetric efficiencies of 20%–35%. Verstraete [32] predicts a decrease in energy usage of 10% for a large long-range aircraft with a tank gravimetric efficiency of about 75% [87]. Brewer and Morris [7] compute energy usage somewhere between those two bounds, with lower energy for hydrogen as the range increases.

Switching to a fuel cell propulsion system is another way to change how efficiently the aircraft uses the fuel. Fuel cells' efficiency may be as much as twice a typical turboprop's thermal efficiency of 25–30% [140,154,190]. The greater efficiency means hydrogen fuel cell aircraft can consume less fuel (measured in terms of energy) than conventional turboprops. The lower energy consumption might be able to compensate for a higher cost of hydrogen than kerosene on a per-energy basis. This can make fuel cells a compelling option for regional hydrogen aircraft even at current technology levels.

Reducing the unit cost of hydrogen (the cost per kilogram) is critical for the competitiveness of hydrogen aircraft [83]. Hoelzen et al. [185] find that in an optimistic hydrogen cost scenario, the operating cost of short- and medium-range hydrogen aircraft would be similar to that of the kerosene-powered baseline. In a pessimistic hydrogen cost scenario, they find that operating costs would double.

The remainder of this section focuses on hydrogen's unit cost components. Most hydrogen aircraft concepts aim to reduce the climate impact of aviation. Accordingly, most of these concepts assume that the hydrogen is produced using electrolysis powered by renewable energy. Thus, this is the type of hydrogen discussed here.

Context is necessary to gain intuition on hydrogen prices. The price of a kilogram of hydrogen must be 90% of the price of a gallon of kerosene (or 3.4 times the price of a liter) to achieve the same cost per unit of energy. For kerosene priced at \$3/gal (\$0.79/L), hydrogen must be \$2.70/kg to be at cost parity on an energy basis.

A breakdown of the cost of each component of renewable LH_2 is shown in Fig. 8.1. Most of the cost of hydrogen by the time it is

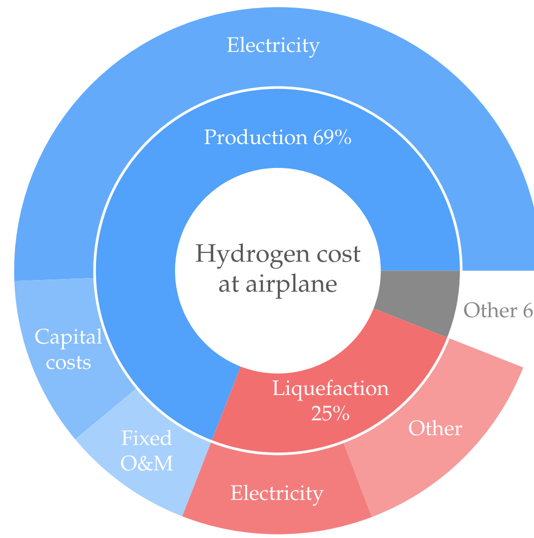


Fig. 8.1. Production is the most significant contributor to the total cost of LH_2, followed by liquefaction. Both electrolysis and liquefaction costs are dominated by the electricity cost .
Source: Data from Hoelzen et al. [185] and more detailed production data from Peterson et al. [191].

delivered to the airplane is the cost of producing it. The production of renewable hydrogen uses a large amount of renewable electricity to drive an electrolyzer, which is a fuel cell in reverse. Electrolyzers are 60%–80% efficient (measured by LHV), so about 1.5 MJ of electricity is required to make 1 MJ of hydrogen [192]. After electrolysis, the hydrogen is liquefied, requiring additional renewable electricity. The hydrogen must also be transported to the airport, stored, and transferred to the aircraft. The production of LH_2 is roughly two-thirds of the final hydrogen cost at the airplane [23,193]. The dominant cost in both electrolysis and liquefaction is the cost of electricity.

As renewable energy resources scale up, their cost is expected to decrease [194]. These resources are also required for electrifying other industries and replacing current fossil fuel electricity generation. There has been some discussion of using electricity in off-peak hours to generate hydrogen [195]. Engineers are looking into using excess energy generated by offshore wind farms to produce hydrogen for selling and smoothing energy production [196,197].

The decreasing cost of hydrogen produced with electrolysis hinges on scaling up hydrogen production volumes and achieving high equipment utilization rates. Increasing the scale of electrolyzer manufacturing enables cost reductions by taking advantage of economies of scale [198]. Increased electrolyzer utilization spreads the capital cost of purchasing the electrolyzer over more hydrogen, which reduces the hydrogen's cost per kilogram [192]. The same principle applies to other equipment, such as liquefaction facilities. In reality, there are times of day when electricity is expensive because of high demand. The increased electrolyzer utilization from producing hydrogen with this expensive electricity does not outweigh the higher electricity cost, so optimal utilizations are below 100% of the time [199].

Several government-funded projects have sought to reduce the cost of hydrogen. In June 2021, the United States Department of Energy launched the Hydrogen Shot program, which aims to reduce the cost of clean hydrogen to $1/kg within a decade [200]. The announcement is vague about what counts as "clean" and how the cost of hydrogen is measured (whether it is only the production cost or the final cost to the consumer, and if it is in gas or liquid form). However, it represents a government intent to spur cost reduction. Mukhopadhaya and Rutherford [58] and Zhou and Searle [201] estimate 2035 and 2050 hydrogen prices to be much higher than $1/kg—roughly between $2 and $7 per kilogram. Their more conservative estimates are for the low-volume production of automotive hydrogen refueling stations, and they consider the cost of hydrogen delivered to the consumer (not just production). The European Union also has a slew of projects to reduce the cost of hydrogen, including the REPowerEU Plan [202] and H2FUTURE [203].

The infrastructure for hydrogen production and distribution to aircraft must be developed from the ground up. Several configurations for this infrastructure are possible. LH_2 could be delivered directly to airports by trucks or pipelines. Alternatively, airports could be supplied with GH_2 that would be liquefied on-site. Finally, hydrogen could be produced at the airport. Postma-Kurlanc et al. [204] estimate that the infrastructure for a large airport will cost hundreds of millions to billions of dollars, depending on the chosen configuration. Other infrastructure strategies are also being pursued. Universal Hydrogen plans to deliver filled hydrogen tanks directly to aircraft and swap them with empty ones. This way, the tank becomes both the distribution system and the onboard storage.

9. Safety and certification

From a safety point of view, hydrogen has advantages and disadvantages. If LH_2 is spilled, it rapidly vaporizes. The gaseous hydrogen then quickly rises due to its low density and dissipates into the atmosphere, reducing the fire hazard [55]. Hydrogen fires are hotter than kerosene's, but because hydrogen does not pool, it does not result in long-lasting fires on the ground like kerosene [205]. This means that the thermal radiation dose from exposure to a kerosene fire can quickly surpass the radiation from a hydrogen fire because of its longer duration, despite the kerosene fire's lower temperature. When Lockheed's Skunk Works was developing the hydrogen-powered CL-400 Suntan, engineers concluded that hydrogen could be handled quite safely [4]. They found it more challenging than expected to induce hydrogen to explode. When it did ignite, the hydrogen fire would quickly dissipate and do less damage than a similar gasoline fire.

However, hydrogen introduces material- and handling-related safety concerns [206]. As discussed in Section 4, hydrogen can permeate and embrittle materials. Material properties also change when cooled to cryogenic temperatures. Sensors, material monitoring techniques, and maintenance procedures must be developed for the hydrogen tank and fuel system so that the aircraft is reliable and safe. Hydrogen is prone to leaking, and its wide flammability range means it could ignite at a wide range of concentrations. These properties make careful handling of hydrogen critical for safety. Hydrogen leak detection and prevention are critical to avoid these flammable scenarios. Engineers must also design the fuel tank and fuel system to keep oxygen from entering, which could create a flammable mixture. This involves constantly maintaining fuel tanks at a pressure higher than ambient to prevent air from entering. Reducing the number of ignition sources as much as possible is vital to reduce the probability that the hydrogen ignites if there is a leak.

In terms of certification, it appears that there are no significant barriers that would prevent a hydrogen aircraft from being certified [189]. The most significant unknowns are future hydrogen storage and distribution regulations. Nangia and Hyde [207] take a conservative perspective, suggesting that the hydrogen storage must be far from the passengers. They believe integrating the tank into the fuselage will not be possible from a safety standpoint. Because no hydrogen aircraft has been certified, questions remain about the requirements. New regulations that apply specifically to hydrogen aircraft systems may be established in the coming years.

In 2017, the Federal Aviation Administration's (FAA) Energy Supply Device Aviation Rulemaking Committee published a report with findings and recommendations for airworthiness standards of hydrogen fuel cells on transport aircraft [208]. The report provides insights into potential future regulatory measures for hydrogen aircraft. The committee recommends to the FAA that hydrogen tanks and fuel lines must be "(1) protected from unsafe temperatures; and (2) located where the probability and hazards of rupture in a crash landing are minimized". It also recommends that fuel lines in the fuselage be "designed and installed to allow a reasonable degree of deformation and stretching without leakage where its leakage could introduce a hazard". They suggest that "hydrogen leakage detection must be installed in any area of the airplane where hydrogen may accumulate and create a hazardous condition". The potential influence of these recommendations on the aircraft configuration is unclear.

10. Climate impact

Reducing the environmental impact of commercial aviation is one of the primary motivations for hydrogen aircraft. Therefore, it is crucial to evaluate the achievable reduction in impact. We focus on three components of life cycle impact that differ from conventional aircraft: hydrogen production, hydrogen transportation, and aircraft emissions. These make up most of the so-called *well-to-wake* emissions.

We must first discuss how climate impact is measured. Conclusions can vary widely depending on the metric used because different climate forcers have different time scales. *Climate forcers* are substances, such as carbon dioxide, that affect the warming or cooling of the Earth's climate. Fig. 10.1 shows the drastic difference in warming behavior between the same emission amount of two climate forcers. The warming from the emission of a long-lived climate forcer, such as carbon dioxide, follows the *cumulative* amount emitted. On the other hand, the warming from the emission of a short-lived climate forcer, such as methane or contrails, tracks the emission *rate*. To stabilize warming, long-lived climate forcer emissions must be driven to zero, while short-lived climate forcers require only constant emissions.

Different metrics exist to quantify these warming effects. *Radiative forcing* (RF) quantifies the warming effect from the emission of a climate forcer at one instance in time and is sensitive to the amount emitted. Radiation from the sun enters Earth's atmosphere and thermal radiation from the Earth exits. Radiative forcing quantifies the net change to this radiation balance from the emission of a climate forcer. It is an instantaneous and globally-averaged measurement.

Effective radiative forcing (ERF) is a modified version of RF that correlates better with the Earth's surface temperature changes. It describes the radiation imbalance after secondary effects (e.g., clouds) have adjusted to the emission.

Global warming potential (GWP) measures the total radiative forcing from a one-ton emission of a climate forcer integrated over a specified period relative to the same value for CO_2. The most commonly used period is 100 years (called GWP_{100}). This metric is useful for comparing the climate impact of different climate forcers. However, it may not correctly weigh the effects of different climate forcers if minimizing peak warming is the objective [210].

Table 10.1
Hydrogen production methods listed from least to greatest climate impact.

Color	Source
Green	Electrolysis powered by renewable energy
Pink	Electrolysis powered by nuclear energy (also known as *purple*)
Blue	Steam methane reforming with carbon capture and storage
Gray	Steam methane reforming
Brown	Coal gasification (also known as *black*)

10.1. Production

Hydrogen can be produced using various methods. Colors are assigned to the most common methods, listed in Table 10.1. The total impact of production methods ranges from near-zero climate impact (green and pink) to higher impact than continued fossil fuel use (brown). Thus, it is essential to consider the source of hydrogen when evaluating the climate impact of hydrogen aircraft.

Using green hydrogen is the ultimate goal for most proposals because it theoretically has zero climate impact. In practice, some renewable energy sources, photovoltaic solar in particular, still emit greenhouse gases when manufactured. Green hydrogen is currently prohibitively expensive compared to other production methods. As discussed in Section 8, most of that cost is from the consumed electricity. However, as the cost of renewable energy decreases and electrolyzer use scales up, green hydrogen costs decrease. Current state-of-the-art electrolyzers convert 70% of the electric energy into the equivalent in hydrogen energy [23]. Further technology improvements may increase this efficiency to 80% or more [211]. Government investments, incentives, and regulations are likely necessary to make green hydrogen-powered aircraft cost-competitive, particularly in the short term [58].

Nearly 80% of hydrogen produced in 2020 is gray or brown, and almost all the rest is a byproduct of other industrial processes [212]. Using gray or brown hydrogen is not an effective way of reducing climate impact and may be more damaging than fossil fuels.

Blue hydrogen is frequently touted as another low-carbon hydrogen source. However, researchers are unsure of its ability to reduce climate impact compared to gray hydrogen. Blue hydrogen also prolongs society's dependence on methane (natural gas) as an energy source. The most significant concern with blue hydrogen is fugitive methane emissions. These emissions could be pipeline leaks or intentional methane venting. Methane is a potent greenhouse gas, so fugitive emissions may overshadow the climate impact reduction of using carbon capture. Blue hydrogen climate impact estimates range from an 85% to 9% reduction in CO_2 equivalent emissions relative to gray hydrogen [213–215].

10.2. Transportation

As we know from Section 4, hydrogen's small molecules make it prone to leaking. This is an existing problem with the natural gas infrastructure (discussed briefly in Section 10.1). If the hydrogen is transported as a liquid, some venting may also be necessary as the LH_2 boils off to avoid exceeding pressure limits.

Hydrogen is not a greenhouse gas; it does not directly interact with the radiation entering or leaving Earth's atmosphere [216]. However, its presence in the atmosphere affects the behavior of other greenhouse gases. Increased hydrogen concentration increases the lifetime of methane, the amount of water vapor in the upper stratosphere, and the concentration of ozone in the troposphere. Derwent et al. [217] estimate the GWP_{100} of hydrogen to be 5 ± 1. However, they do not include the effects of H_2 emissions on stratospheric water vapor. When those are considered, the GWP_{100} increases to 11 ± 5 [218]. Research quantifying the effects of direct hydrogen emission is limited, so uncertainties remain.

Warwick et al. [218] estimate leakage rates between 1 and 10% of the hydrogen produced. Assuming a lower leakage rate, the climate impact relative to the impact from hydrogen production and consumption would be low [217,219]. However, the climate impact of a higher leakage rate could be significant. Combusting fossil fuel also emits hydrogen, so reducing fossil fuel use offsets some of the hydrogen leakage and venting emissions [218,220]. A leakage rate approaching 10% is unlikely because it would be expensive and unsafe [218].

Transporting the hydrogen in its pure form is not the only option. Another approach is to convert the hydrogen into ammonia for transport and convert it back to hydrogen at its destination. Ammonia is already widely distributed as a fertilizer for agriculture. It is liquid at room temperature and only 10 bar, simplifying handling. Transporting hydrogen via ammonia would enable using existing ammonia distribution by pipeline, ship, rail, and truck [221], circumventing the need for an entirely new hydrogen distribution infrastructure. However, the energy losses from the chemical conversions required by this transportation approach may make it uncompetitive [222]. Furthermore, ammonia damages ecosystems through acidification and

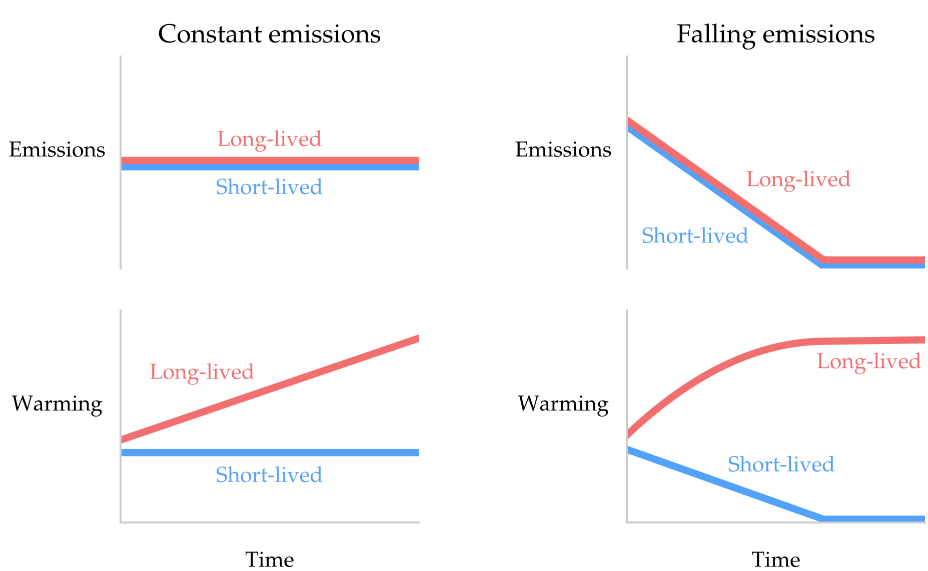


Fig. 10.1. Warming from an emission depends on the climate forcer's lifetime.
Source: Adapted from Allen et al. [209].

eutrophication [223], and poses a risk to human health when released into the atmosphere [224]. These problems could be exacerbated if the ammonia distribution network was expanded.

10.3. Aircraft emissions

The climate impact of conventional aircraft is dominated by carbon dioxide (CO_2), nitrogen oxides (NO_x), and contrails [186]. Carbon dioxide is a long-lived climate forcer and the most influential human emission contributing to climate change [225]. NO_x is produced by high-temperature reactions, such as reactions in gas turbines and SOFCs. It impacts warming indirectly by affecting other greenhouse gas behavior.

Water vapor and other particles emitted by engines form contrails, which may be aviation's most significant impact on the climate. Soot and sulfur emissions contribute to aviation's climate impact, but their effect is much smaller than those already mentioned. Soot emissions have a climate warming effect, sulfur and sulfate aerosols have a cooling effect, and both affect contrail formation. Fig. 10.2 shows the estimated contribution of each emission on radiative forcing in 2018.

Hydrogen aircraft development is motivated by the desire to drastically reduce aviation's climate impact. However, minimizing climate impact is rarely an objective in commercial aircraft design. Instead, airframers aim to minimize a combination of aircraft acquisition and operating costs. Proesmans and Vos [226] design climate- and cost-optimized medium-range narrowbody aircraft and show the difference between the two. They find that optimizing a kerosene aircraft for minimal climate impact increases the cash operating cost by 7% compared to the cost-optimized design. For the hydrogen aircraft, this value increases to 15%, primarily because of a decrease in cruise altitude to reduce contrail formation. Nonetheless, the cost-optimized hydrogen aircraft reduces climate impact by 71% compared to the cost-optimized kerosene aircraft.

In the following subsections, we describe how each major climate forcer from conventional aircraft changes when switching to hydrogen propulsion. CO_2 emissions are eliminated, and NO_x emissions may be reduced or eliminated. The behavior and properties of contrails change when switching from kerosene to hydrogen propulsion. Some predict these changes would result in a lower climate impact from contrails than conventional aircraft, but significant uncertainties remain.

10.3.1. Carbon dioxide

Because there is no carbon in the fuel, hydrogen aircraft do not emit CO_2. Eliminating carbon dioxide emissions would be a significant breakthrough because CO_2's long lifetime means its effects on the climate persist for millennia [227]. From a climate perspective, eliminating CO_2 emissions is the greatest motivation for hydrogen aircraft. The absence of carbon or sulfur in the fuel also means that hydrogen aircraft produce no soot or sulfur emissions.

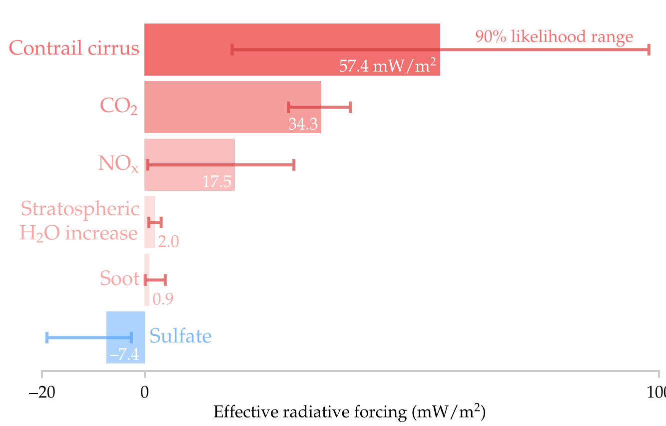


Fig. 10.2. Global aviation's effective radiative forcing in 2018 was dominated by contrail cirrus, CO_2, and NO_x emissions (data from Lee et al. [3]). Soot and sulfate emissions may also impact cloud formation, but the values are highly uncertain.

10.3.2. Nitrogen oxides

NO_x is currently aviation's most significant climate forcer after contrail cirrus and carbon dioxide. It is an *indirect greenhouse gas* because it contributes to warming only through its effect on other gases [227]. NO_x produces ozone, which is a greenhouse gas. NO_x also reduces the lifetime and concentration of methane. Methane is a greenhouse gas, so reducing its lifetime in the atmosphere has a cooling effect. The warming from increased ozone outweighs the cooling from the effects on methane, resulting in a net warming effect.

Fuel cells produce virtually no NO_x [111], though higher temperature ones, such as SOFCs, do produce some. Hydrogen combustion engines emit NO_x, but the amount may be reduced by taking advantage of hydrogen's combustion properties, as discussed in Section 5.1. Considering NO_x emissions in the combustor design is critical if aviation's climate impact is to be reduced.

10.3.3. Contrails

Contrails and associated contrail cirrus clouds are the greatest unknown and potentially the most significant contributor to the climate impact of hydrogen aircraft. These and other cloud effects are collectively known as aircraft-induced cloudiness (AIC). Their impact is short-lived, lasting at most 10s of hours [228]. These cloud formations reflect short-wave solar radiation into space during the day, which has a cooling effect. On the other hand, they prevent some long-wave thermal radiation emitted by the Earth from making it out of the atmosphere. This results in a net warming effect of AIC [229].

Contrails form when hot aircraft exhaust containing water vapor cools, causing the air to become saturated. Beyond the saturation point, the remaining water vapor freezes, forming small ice crystals. Soot and other particles in the exhaust act as nucleation sites for the formation of ice crystals. Contrail formation requires additional moisture to be available after the local relative humidity has reached 100%. A contrail is produced when the remaining moisture freezes into ice crystals. The Schmidt–Appleman criterion describes the threshold temperature below which these conditions are met based on the ambient conditions and engine exhaust properties [230–232]. The ambient humidity determines how long the contrail lasts. If the ambient air is not supersaturated with respect to ice, turbulent mixing dissipates the contrails (see Fig. 10.3). If it is, contrails can persist for hours. Much of the water content in persistent contrails comes from the surrounding atmosphere rather than from the water vapor in the engine exhaust. Schumann et al. [233] predict that the median mass of water in persistent contrails is in the order of 1,000 times greater than the mass of water initially emitted by the aircraft.

Contrails can spread from their original linear shape into contrail cirrus clouds indistinguishable from natural cirrus clouds, wispy high-altitude clouds made of ice crystals. Burkhardt and Kärcher [228] estimate that the radiative forcing from contrail cirrus is nine times greater than from linear contrails alone. This would make them the most significant element in the total radiative forcing from aviation.

Only in the past couple of decades have atmospheric scientists uncovered the significant climate impact of contrail cirrus. Contrails were mentioned only once in the Second Assessment Report [234] released in 1995 by the Intergovernmental Panel on Climate Change (IPCC). Linear contrails received more attention in the IPCC's Third Assessment Report [235], released in 2001. Scientists realized that cirrus cloud coverage was greater and more frequent in locations with high air traffic [236,237]. They also discovered thin layers of ice crystals high in the atmosphere that could contribute to warming and might be due to contrails [238]. At the time, the contribution of these phenomena to radiative forcing was poorly understood. By the IPCC's

Fig. 10.3. Larger ice particles in contrails fall on average 700 m [233] to altitudes where they sublimate back into water vapor. Other particles disappear once atmospheric mixing moves them to locations with lower humidity. The larger falling ice crystals can be seen in this photo as streaks directly below the linear contrail (first author's photo).

Sixth Assessment Report [239] in 2021, researchers predicted that the combined effect of contrails and aviation-induced cirrus was the most significant contributor to aviation's effective radiative forcing, albeit still with low confidence.

Uncertainty remains about the climate effects of contrails. Contrail cirrus and natural cirrus clouds appear identical, and some contrail cirrus are so thin that they cannot be detected by satellites or from the ground [228]. These factors make it challenging to quantify their effects by observation. To quantify contrails' impact, most researchers use meteorological data to predict when they will form. Recall that contrail formation and persistence depend on atmospheric temperature and humidity. Temperature data is reliable, but obtaining accurate humidity data is more challenging. By comparing the combined meteorological data to data from radiosondes, Agarwal et al. [240] show that models may overestimate the radiative forcing from persistent contrails by 100%–250% because the meteorological data often overpredicts the humidity. This results in an overprediction of the persistence of contrails.

Finally, contrails have secondary effects that are challenging to quantify. As previously mentioned, most of the water in persistent contrails is taken from the surrounding atmosphere rather than the engine exhaust. The lower humidity results in thinner contrails with higher mean age and suppresses the formation of natural cirrus clouds [233]. This tends to partially offset warming from aircraft-induced cloudiness. Another secondary effect is from soot, which provides nucleation sites for cirrus clouds [241]. This can cause cirrus clouds to form before they would occur naturally. These effects can have either a warming or cooling effect, depending on the atmospheric conditions [242].

Hydrogen combustion in a turbofan changes the contrail equation in two ways. Firstly, using hydrogen produces 2.6 times more water than kerosene per unit of energy consumption. Secondly, hydrogen produces no soot or sulfate aerosols. The increased water vapor emissions cause contrails to form more frequently. Schumann [232] estimates that the threshold temperature below which contrails form is 10 K higher for hydrogen aircraft than for conventional kerosene aircraft. This causes contrails to form at a wider range of altitudes. In 1957, NASA flew a B-57 aircraft with one of the two engines modified to burn hydrogen. The pilots observed that the hydrogen-burning engine produced contrails when the kerosene-powered engine did not [4].

The climate impact of increased contrail formation frequency of hydrogen aircraft is counteracted by the absence of soot and other particles in the exhaust. Eliminating soot and particle emissions leads to fewer, larger ice crystals [232,243–245]. The contrails made up of these larger ice crystals have a smaller optical depth and shorter lifetime, reducing their warming effect. Ponater et al. [246] estimate that the changes from eliminating soot outweigh the increased formation frequency from increased water vapor emission, reducing the radiative forcing from contrails compared to conventional aircraft. Eliminating soot emissions would also remove the artificial nucleation sites produced by today's aircraft that cause natural cirrus clouds to form before they otherwise would.

Fuel cells may produce no contrails or contrails with a higher impact than those from turbofans, depending on how the propulsion system is designed and operated. Without processing the fuel cell's exhaust, Gierens [247] estimates that fuel cells produce contrails more frequently than hydrogen combustion engines. This is because they produce a large amount of water vapor emissions, and the exhaust's static temperature can be low. Similarly to hydrogen combustion engines, the contrails from fuel cell propulsion are expected to have a smaller optical depth and decreased lifetime compared to those generated by kerosene engines. Unlike a turbofan, a fuel cell's exhaust does not generate thrust. This means the performance penalty of extracting water from the exhaust is lower than for turbofans. Universal Hydrogen has mentioned that it is possible to reduce contrail formation by storing the water vapor emissions and releasing them when onboard atmospheric sensors detect that persistent contrails are less likely to form [248]. However, collecting and storing the water onboard would quickly increase the aircraft weight because the mass flow rate of water produced is nine times the mass flow rate of hydrogen consumed.

In the future, the climate impact of contrails could be reduced by adjusting the cruise altitude or route of flights [249]. This would require more advanced air traffic management and better atmospheric modeling to predict contrail formation. If this strategy was used for kerosene aircraft, they would burn more fuel when cruising at suboptimal altitudes, emitting more CO_2. The benefits of reducing a short-lived climate forcer (contrails) at the cost of increasing a long-lived climate forcer (CO_2) are disputed. Because hydrogen aircraft do not emit CO_2, there is a greater incentive to optimize hydrogen aircraft operations to reduce contrails.

Research is ongoing to understand the formation and climate impact of aircraft-induced cloudiness, including experimental contrail measurements at altitude. The ML-CIRRUS project in Germany instrumented a Gulfstream 550 aircraft to study the properties and behavior of cirrus clouds [250]. Data collected during the project helped scientists validate their models and better understand the climate effects of contrail cirrus clouds. Airbus UpNext announced the Blue Condor program in partnership with DLR to measure the contrail properties of hydrogen-burning and kerosene-burning turbojet engines using a chase aircraft [251].

10.3.4. Other emissions

The water vapor that does not form contrails is only a minor contribution to the climate impact [227]. Its effect is negligible when emitted below 8–10 km, where clouds and precipitation occur. Above that, its warming effect is still small but not negligible because the background water vapor concentration is lower.

Most hydrogen aircraft concepts do not vent H_2 during the flight, but it may be necessary sometimes. As discussed in Section 10.2, hydrogen indirectly affects greenhouse gases, which results in net warming. However, this effect is likely negligible if venting hydrogen is avoided.

11. Conclusions

Hydrogen-powered aircraft are a proposed solution to sustain the civil aviation industry in an environmentally-responsible way. Many researchers and engineers consider them the most viable long-term alternative to kerosene-powered aircraft. Hydrogen aircraft are not necessarily restricted to long-term ambitions. H2FLY and Deutsche Aircraft, Universal Hydrogen, and ZeroAvia are pursuing hydrogen-powered regional propeller aircraft to fly passengers by the end of this decade.

Hydrogen aircraft require much more research and development, but there appears to be a path to technological feasibility.

One of the most significant technological challenges is storing and handling hydrogen onboard. Compressed GH_2 storage may be sufficient for small aircraft, but LH_2 is crucial for long-range aircraft to limit the tank volume and weight. For tank gravimetric efficiencies greater than about 55%, which are possible with LH_2, we estimate that hydrogen aircraft energy consumption decreases relative to kerosene aircraft as the mission range increases. Although LH_2 tanks are routinely used in rockets, tanks for aircraft need longer lifetimes and lower boil-off rates. In addition, aircraft fuel systems must handle lower mass flow rates and more cycles than rocket fuel systems. In the long term, vacuum-insulated LH_2 tanks might be the most effective hydrogen storage solution for aircraft. Research efforts should focus on reducing their weight with new materials, designs, and manufacturing techniques. Integral tanks are another way to reduce the weight of onboard hydrogen storage. Conformal tanks might be advantageous if the weight penalty is outweighed by airframe drag reduction.

Hydrogen aircraft can use conventional gas turbines for propulsion. Advanced gas turbines convert fuel to mechanical work at efficiencies of around 40%. Using gas turbines leverages existing knowledge, design tools, and manufacturing techniques. A combustor designed for hydrogen's thermal and combustion properties is the only substantial change to the turbomachinery. The thrust-specific energy consumption of hydrogen turbofans is expected to be about the same as that of kerosene-powered turbofans. Further improvements are possible by taking advantage of hydrogen's unique properties. Cryogenic LH_2 can be used as a heat sink to move heat to more useful locations in the engine. Condensing some of the water vapor in the exhaust and injecting it back into the engine cycle could be beneficial.

Hydrogen fuel cells are an alternative to combustion-based propulsion. They convert hydrogen into electricity at efficiencies greater than 50%. The electricity then powers electric motors connected to propellers or ducted fans. Aircraft with fuel cell propulsion systems can be true zero-emission aircraft if contrail formation is avoided by managing the water exhaust. The specific power, efficiency, and durability of aviation-specific fuel cells should be improved. Depending on the aircraft and fuel cell designs, a fuel cell propulsion system for a narrowbody transport aircraft is estimated to be three times heavier than an equivalent turbofan propulsion system. Fuel cell-powered aircraft require carefully designed thermal management systems to mitigate the weight and drag penalties. Innovative designs may take advantage of the heat produced by the fuel cell for other purposes, such as managing the LH_2 storage.

Most proposed hydrogen aircraft concepts use the conventional tube-and-wing configuration because the industry has tube-and-wing-specific design tools and expertise. However, the strong incentive to reduce the weight and drag penalties of onboard hydrogen storage may push aircraft designs toward unconventional configurations, such as blended wing bodies.

Hydrogen has safety benefits over kerosene. It rapidly vaporizes and rises if it leaks, so it does not pool and create standing fires on the ground like kerosene. However, hydrogen has a wider flammability range, making igniting easier. Hydrogen aircraft certification requires thorough leak detection, isolation from ignition sources, and crash-safe structural designs.

From a climate perspective, hydrogen aircraft would have a drastically lower impact than conventional aircraft if the hydrogen is produced with renewable energy, such as wind, solar, or nuclear energy. Hydrogen-powered aircraft produce no carbon dioxide and can reduce or eliminate NO_x emissions, depending on the propulsion system. The impact of persistent contrails and contrail cirrus is still uncertain. However, recent estimates predict their impact to be less than the impact of contrails and contrail cirrus from kerosene-powered aircraft. The predicted contrail cirrus impact reduction is because hydrogen combustion exhaust contains no soot or sulfate emissions, which changes the contrail ice crystal and climate warming properties. The impact of contrails may also be reduced by routing flights around regions where persistent contrails are likely to form. Although hydrogen aircraft would produce more water vapor, direct water vapor emissions (excluding contrails) are expected to have only a minor climate effect, especially when emitted below 8 km.

The economic cost of hydrogen aircraft is still unknown, though most studies predict higher operating costs than today's aircraft. Some of the cost increase is due to higher acquisition and maintenance costs associated with hydrogen storage. Lighter LH_2 tanks help reduce the amount of fuel the aircraft consumes. The cost of electricity dominates the unit cost of green hydrogen. The decreasing trend in renewable electricity prices will reduce the cost of green hydrogen. Increasing the scale of green hydrogen production would also reduce its unit cost. However, these changes alone may not make green hydrogen cost-competitive with kerosene in the near future.

Transitioning to hydrogen-powered air transportation requires massive investments. Private companies and government-funded projects are designing and flying prototypes, but more funding and engineering development is needed. Together with governmental pressure and industry-wide collaboration, these efforts could steer aviation toward a climate-compatible future based on hydrogen.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Flight Path and Wing Optimization of Lithium-Air Battery Powered Passenger Aircraft

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The design of electric-powered aircraft for use in the commercial aviation sector is a complex, heavily multidisciplinary problem that requires careful consideration of power and energy tradeoffs, in addition to more traditional performance metrics. A multidisciplinary, multifidelity aircraft design code called SUAVE (Stanford University Aerospace Vehicle Environment) has been developed in part to address these considerations. This paper explores the application of this design code towards a passenger aircraft at the commercial scale, with the wing, flight path, and an electric propulsion system designed and optimized for a prescribed number of passengers at a variety of different ranges. Additionally, aircraft weight sensitivities to battery technology, motor technology, as well as takeoff and landing constraints were evaluated, and their relative feasibility assessed.

Nomenclature

AoA	angle of attack
C	C rate the battery is discharged at
Esp	specific energy
f	factor in empirical discharge loss
F	Faraday Constant
G_0	Gibbs Free Energy
h	altitude
I	current
P	power
P_{motor}	motor power
Psp	specific energy
R	effective resistance
R_0	empirical resistance factor
S_{ref}	wing reference area
TOFL	Take Off Field Length
LFL	Landing Field Length
V	velocity magnitude
V_0	reaction potential
x	state of charge
α	twist
Λ	sweep

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Subscripts

1,2,3...	segment number
rc	root chord
tc	tip chord

I. Introduction

Fuel costs, along with demand for commercial air travel have been rising dramatically in the recent past. In particular, fuel costs have doubled over the past 10 years, having risen to account for approximately 50% of airline operating costs for wide-body airplanes and to 30% for regional jets.[1] Furthermore, demand is expected to increase by 1.4 to 3 times by 2025 from 2004 levels.[2] This increased demand for air travel will result in enormous additional greenhouse gas emissions, in the absence of substantial reductions in overall fuel burn.[3] Additionally, electric energy only costs a fraction of the equivalent amount of fossil fuel energy.[4] Therefore, the achievement of electrically-powered aircraft has powerful economic as well as environmental incentives.

As a result, there has been considerable interest in the design of electrically-driven aircraft, particularly in the case of fuel cells and batteries.[5–7] One of the primary advantages of batteries is due to the perceived relative lack of infrastructure required to implement vis. a vis. fuel cells, in particular, liquid hydrogen fuel cells. However, present-day battery technology does not allow for the development of commercial-scale all-electric aircraft, due to limitations in the specific energy, and in some cases specific power of lithium-ion batteries. Nonetheless, lithium-air batteries, initially, appear much more promising, with estimated specific energies ranging from 1000-2000 W-h/kg, and specific powers from .4-.67 kW/kg.[8,9] Lithium-air batteries were expected to be commercially available by 2030, although recent studies highlight significant design issues that may call this date into question.[9,10] One unique aspect of a lithium-air battery that must be taken into account in the design process is that, as the battery discharges, oxygen particles collect on the cathode, which in turn, causes the battery to gain mass.[11] For larger batteries (such as what may potentially be used for commercial aviation), this mass gain may be considerable.

II. Methodology

Several issues must be examined in the design of an electric aircraft. Firstly, mass tends to be a primary metric of feasibility due to the fact that electrical components tend to be much heavier than their fossil fuel-based equivalents. Modern commercially available batteries in particular suffer from possessing a specific energy two orders of magnitude lower than Jet A ($\sim$ 130 W-h/kg vs. 12,000 W-h/kg, respectively).[12] Lithium-air batteries, are much more promising, particularly at the more optimistic specific energy estimate of 2000 W-h/kg. Unfortunately, this is still only 1/6 that of Jet A.

Nonetheless, several factors can improve the overall feasibility of these designs. Firstly, electrical systems tend to be more energy efficient than combustion-based systems. Thus, some of this gap in capability may be closed based on smaller energy conversion losses. Secondly, because much of the increased demand in air travel is at shorter ranges, electric aircraft need not be designed to match all of the capabilities of current commercial aircraft, and could meet this demand more easily by reducing the overall range. Thirdly, because battery-electric systems are thermodynamically different than standard combustion-based systems, the entire aircraft may be designed to fly at a lower altitude; commercial aircraft fly at the coldest part of the atmosphere primarily in order to improve the Carnot efficiency of the propulsion system; because a battery-motor-ducted fan based system is not a heat engine, there is no significant advantage to flying higher, at least from a strictly thermodynamic perspective. Thrust requirements for takeoff and landing may offset this, however, as the propulsor may grow with these requirements, which changes the optimal operating altitude from a propulsive standpoint.

Designing the aircraft for a lower altitude allows for the redesign of several of the aircraft components to reduce overall systems weight. For instance, because the pressure differential experienced by the fuselage is smaller at lower altitudes, the fuselage can be designed with less structural reinforcement, reducing the overall weight in cases where pressure loads dominate overall fuselage sizing structural requirements. Furthermore, due to the higher temperatures, the aircraft could operate at a lower Mach Number while maintaining the same cruise velocity, reducing wave drag; thus, the wing may be unswept, which would also lower the structural weight. Finally, the increased freestream dynamic pressure on the aircraft allows for the wing and tail to be "shrunk," relatively speaking, which further decreases the overall aircraft weight.

In addition to energy constraints, one has to account for power constraints in designing electric aircraft. Lithium-air batteries, for instance, are expected to have a relatively low specific power, on the order of .67 kW/kg. One can significantly improve the feasibility of these designs by shaping both the flight profile and the wing to account for this.

To evaluate these designs and close on families of optima, the Stanford University Aerospace Vehicle Environment (SUAVE), was used. SUAVE is a multifidelity, multidisciplinary conceptual design tool that has been developed to address the evaluation, feasibility, and optimization of unusual aircraft designs, such as electric aircraft. SUAVE evaluates a given aircraft for a given mission by solving the equations of motion at a finite number of time steps based on mission constraints and prescribed aerodynamics and propulsion models.

The baseline aircraft evaluated here is a regional passenger jet, with a design payload of 114 passengers and design range of about 2400 nautical miles. This aircraft was chosen largely because, in the initial conceptual design process, it was thought that aircraft carrying a relatively smaller payload (as opposed to, for instance, a 747-class aircraft) would be easier to develop considering the significant weight penalties associated with even optimistic battery estimates.

In this study, the fuselage nose and tailcone ratios were reduced from 2 and 3 to 1.5 and 1.8 respectively (to reduce wetted area, which the lower operating altitude allows based on a lower drag divergance Mach Number[13]), while the turbofans and jet fuel were replaced with ducted fans, electric motors, and lithium-air batteries. Electric motor mass and ducted fan mass were estimated based on the state of the art (SoA) scaling correlation shown in Figure 1.[14]

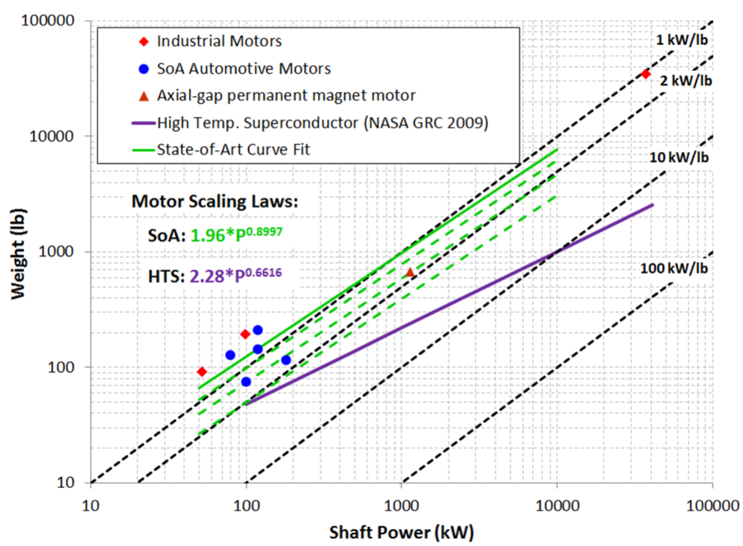


Figure 1: Electric Motor Scaling Correlation

Except when explicitly stated otherwise, all aircraft in this paper were designed using the state of the art (SoA) curve fit shown in Figure 1 to determine electric motor mass. Some interest has been shown in the relative weight gains one may experience using high temperature superconducting (HTS) motors, as they possess a considerable improvement in specific power, although their design and implementation is somewhat more complicated.[5,15] This paper will also look at the potential gains in aircraft mass one can accomplish when they are optimized using the HTS motor fit shown in Figure 1. Boundary layer ingestion may result in additional efficiency gains.

Battery discharge losses were modeled using an empirical discharge model developed in reference,[16] which is repeated below.

$$f = 1 - \exp(-20x) - \exp(-20(1-x)) \tag{1}$$

$$R = R_0(1 + C \cdot f) \tag{2}$$

$$P_{discharge} = I^2 \cdot R \tag{3}$$

Additionally, the mass gain rate of the aircraft from battery discharge was based on the chemical reaction of lithium with oxygen, as seen below.[9]

$$2Li + O_2 \Rightarrow Li_2O_2, G_0 = -606.68kJ \tag{4}$$

$$\dot{m} = \frac{MW_{O_2}}{V0_{Li_2O_2} \cdot F} \cdot P \tag{5}$$

All other component weights were estimated based on traditional sizing correlations imported from PASS (Program for Aircraft Synthesis Studies) into SUAVE.[17] Aerodynamic properties were calculated via a weissinger vortex lattice method with profile drag correlations. The wing reference area, twist at the root and tip, sweep, and motor power were taken as input variables for an optimization scheme, while the taper and aspect ratio were maintained as equal to the baseline regional jet airplane (.28 and 8.3, respectively). The tail was sized based on a correlation from Raymer.[18] Furthermore, cruise velocity from the baseline aircraft was maintained. The cruise range as well as climb and descent profiles were also modified and optimized, based on a baseline flight profile with five climb segments and three descent segments. For the climb segments, the final altitude of each segment as well as the magnitude of the aircraft velocity at each segment were modified while maintaining the vertical climb rates; the mission solver then determined the throttle and angle of attack of the aircraft needed to match these parameters. Each descent segment maintained the baseline velocity magnitude and descent rate, while modifying the final segment altitudes, noting that the final segment altitude would always be sea level. Table 1 shows all of the design variables for the vehicle, while Table 2 depicts the flight profile design variables. Table 4 in the Appendix displays the vertical climb and descent rates along with the descent velocities, for reference.

Table 1: Aircraft Design Variables

α_{rc}	α_{tc}	Λ	P_{motor}	S_{ref}

Table 2: Mission Design Variables

h_{climb_1}	h_{climb_2}
h_{climb_3}	h_{climb_4}
h_{climb_5}	V_{climb_1}
V_{climb_2}	V_{climb_3}
V_{climb_4}	V_{climb_5}
$h_{descent_1}$	$h_{descent_2}$
$cruise\ range$	

An iterative scheme was developed to determine the maximum power required, along with the battery energy required to run the the mission based on the number of passengers, and aircraft component weights, including wing, battery and motor weights estimated for this particular aircraft and mission. Note that the battery accumulates a significant amount of weight throughout the mission; as a result, aircraft components were sized assuming a fully discharged battery, while the equations of motion took into account the increasing mass. The aircraft and mission were then optimized to determine the minimum possible landing weight. Design variables were constrained to ensure washout, maintain a target vehicle range, limit takeoff and landing field lengths, limit twist, as well as ensure consistency in the flight profile. The constraints can be seen below.

$$-5^\circ \leq \alpha_{tc} \leq \alpha_{rc} \leq 5^\circ \tag{6}$$

$$0^\circ \leq \Lambda \leq 30^\circ \tag{7}$$

$$0\ km < h_{climb_1} < h_{climb_2} < h_{climb3} < h_{climb4} < h_{climb5} < 13\ km \tag{8}$$

$$h_{descent_1} > h_{descent_2} > 0\ km \tag{9}$$

$$-30^\circ \leq AoA \leq 30^\circ \tag{10}$$

$$TOFL \leq 1500m \tag{11}$$

$$LFL \leq 1500m \tag{12}$$

$$range \geq target\ range \tag{13}$$

III. Results

These aircraft, with proper initial guesses, allow for designs that may be somewhat comparable in weight to the baseline regional jet, depending on the range. Note that shaping the mission flight profile for these designs was crucial to ensure feasible weight breakdowns; it was found that merely replacing the propulsion system with a lithium-air based propulsion system, and running the same profile caused the sizing loop to diverge, largely due to the low specific power of lithium-air batteries. Choosing a new initial guess for the profile allowed for substantial reductions in gross landing weight. A CAD model of a representative electric aircraft (with a box representing the required battery volume) can be seen in Figure 2 below, along with a component weight breakdown, compared to the baseline in Figure 3.

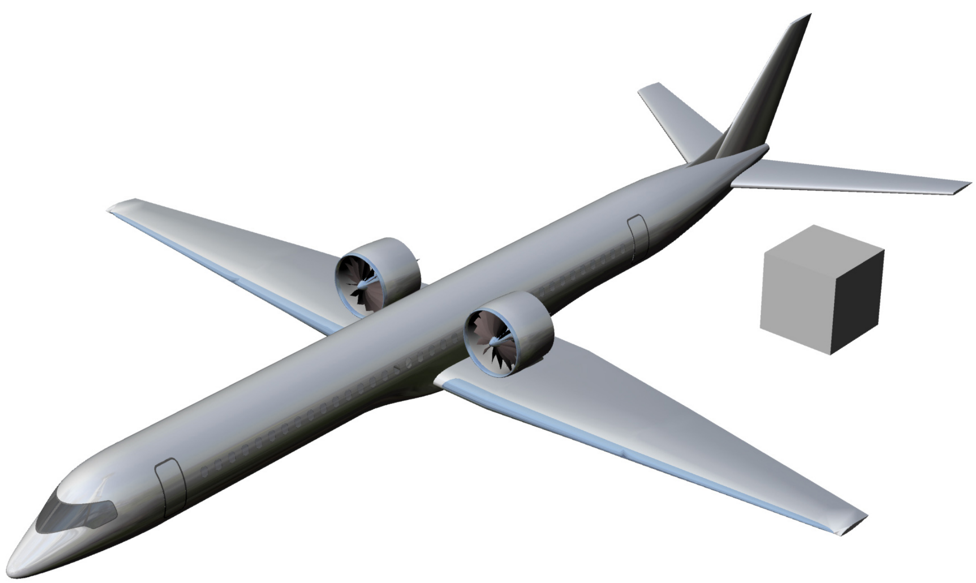
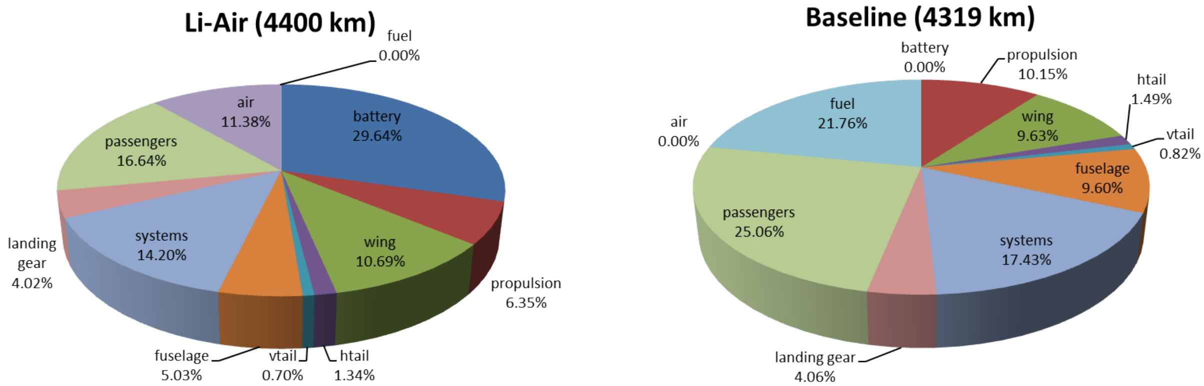


Figure 2: 4400 km Design (2000 W-h/kg .67 kW/kg battery)



(a) Max Landing Weight=67464kg
Gross Takeoff Weight=59786 kg

(b) Gross Takeoff Weight=52300 kg
Landing Weight=40400kg

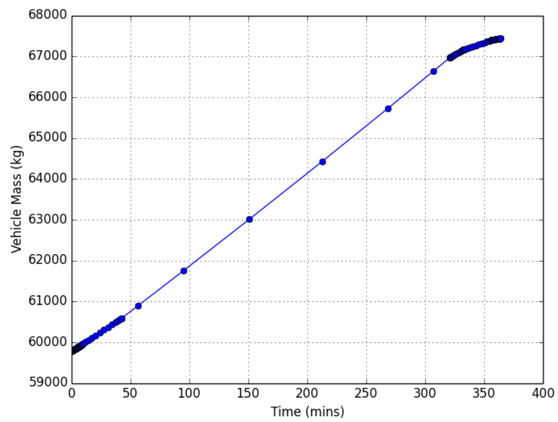
Figure 3: Weight Breakdown

It is immediately apparent that the battery takes up a very substantial portion of the aircraft, both from mass as well as volumetric standpoints, which must be taken into account for higher-level analysis and design. In particular, a blended-wing body design may be an effective solution to the apparent volumetric issues seen here. Note that the wing is completely unswept for this particular design. The fuselage is substantially lighter as well, comparably speaking (largely as a result of the lowered cruise altitude), which contributes to the overall feasibility of the design. Finally, one should bear in mind that distributed propulsion may lead to further reductions in weight; electric motor specific power is not particularly sensitive to scale. Thus, one may theoretically distribute ducted fans along the span of the wing to enable additional boundary layer ingestion benefits that are not currently modeled. Table 3 shows a comparison of the design variables for the baseline turbofan aircraft and an optimized electric aircraft.

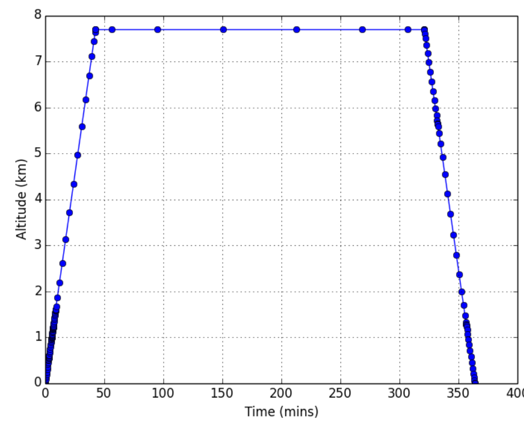
Table 3: Aircraft Comparison

	Baseline Aircraft	Electric Aircraft (4400km)
h_{climb_1}	3.048 km	0.543 km
h_{climb_2}	3.657 km	0.994 km
h_{climb_3}	7.620 km	1.212 km
h_{climb_4}	9.754 km	1.601 km
h_{climb_5}	11.28 km	7.699 km
$h_{descent_1}$	9.31 km	5.631 km
$h_{descent_2}$	1.28 km	1.278 km
V_{climb_1}	138 m/s	125.5 m/s
V_{climb_2}	168 m/s	173.9 m/s
V_{climb_3}	200 m/s	180.9 m/s
V_{climb_4}	230 m/s	188.0 m/s
V_{climb_5}	230 m/s	178.4 m/s
α_{rc}	2 °	-.322 °
α_{tc}	0 °	-.341 °
Λ	22°	0.01 °
S_{ref}	92 m^2	143.8 m^2
$cruise\ range$	3426.2 km	3472.4 km
P_{motor}	N/A	7.45 MW

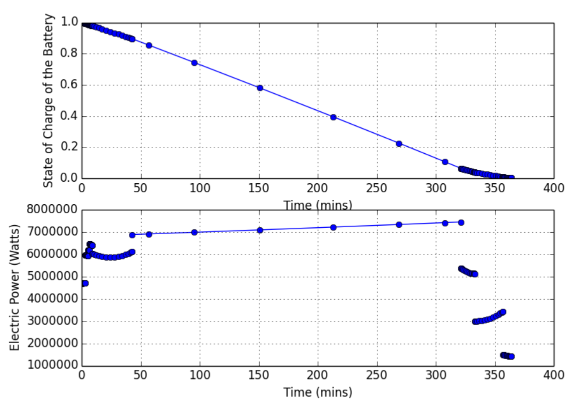
The tradeoffs between increased engine thrust, wing area, and field length were key in determining the final design of the electric aircraft; the cruise dynamic pressure of the electric design is 1.56 times that of the baseline aircraft, while the maximum mass of the aircraft is 1.25 times that of the baseline. Thus, in the absence of field length constraints, the wing area should be smaller. However, the landing mass is 1.67 times that of the baseline, due to the mass accumulation of the battery, which means that, to maintain landing field length requirements (Equation 12), the wing area needs to be increased. In addition, the optimizer determined that increased wing area carries a much smaller weight penalty than increased motor mass, so the takeoff field length constraint (Equation 11) also factored into the final designs. To maintain cruise efficiency, wing twist was decreased slightly. Furthermore, due to the lower Mach Number(.78 vs. .74), the wing became completely unswept. Note that the electric aircraft climbs at a much slower velocity to reduce power demands on the battery. Sample mission outputs from SUAVE for this particular design can be seen in Figure 4, while a flight profile of the baseline aircraft along with the electric version can be seen in Figure 5.



(a) Vehicle Mass



(b) Altitude



(c) Power

Figure 4: Sample Aircraft Mission Outputs

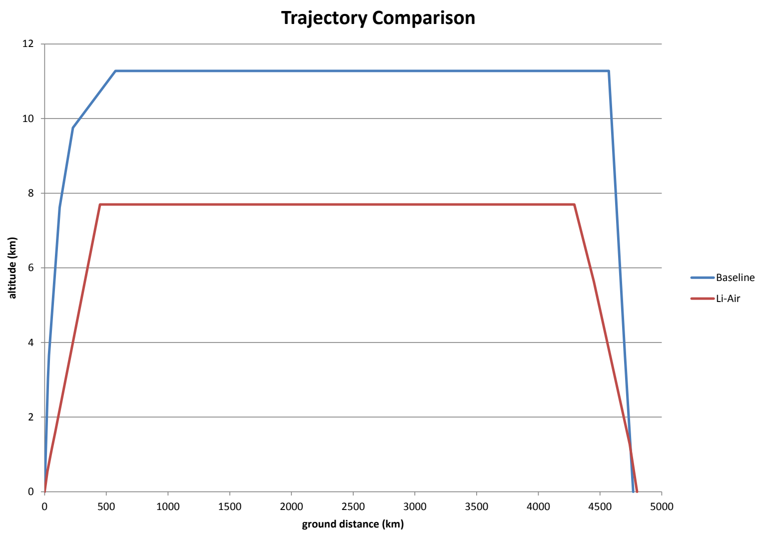


Figure 5: Aircraft Flight Profiles

These results show a number of interesting trends. Firstly, the cruise altitude is substantially lower than the baseline cruise altitude of 11.28 km, which enables the comparatively smaller fuselage weight shown in Figure 3. Secondly, note the relatively gentle power curve, especially when compared to that of the baseline, shown in Figure 10 in the Appendix, which again, was critical in ensuring convergence in the sizing loop. This trend can also be seen from the flight profile of the two vehicles, where the electric aircraft climbs and descends at a significantly lower rate than the baseline aircraft. Furthermore, battery mass accumulation has a significant impact on both power consumption, as well as in changing the angle of attack to maintain altitude and trim. Figure 6 depicts the landing weight, takeoff weight, as well as the baseline gross takeoff weight, highlighting the weight penalties for increasing the range.

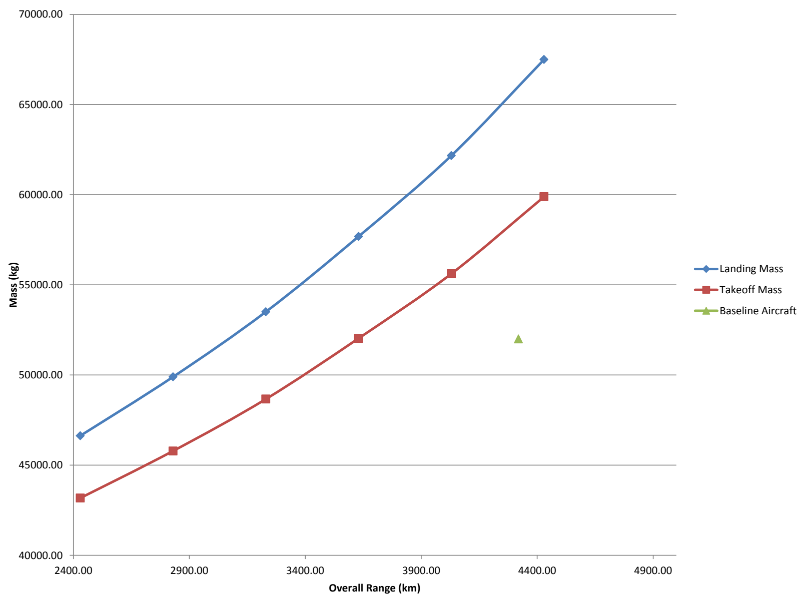


Figure 6: Aircraft Designs vs. Target Range

Of note here is that, particularly at shorter ranges, these electric aircraft have overall weights that compare favorably to the baseline aircraft. Furthermore, because much of the increased demand for commercial air travel is at shorter ranges, the design of these aircraft may be able to fill a niche role in the future aircraft market. However, with recent setbacks in lithium-air research, the 2000 W-h/kg specific energy value may be overly optimistic. Figure 7 shows a plot of landing weight of an optimized configuration vs design range at specific energies of 2000, 1500, 1000, 500, 250 W-h/kg, as well as a plot of 2000 W-h/kg designs with relaxed field length constraints.

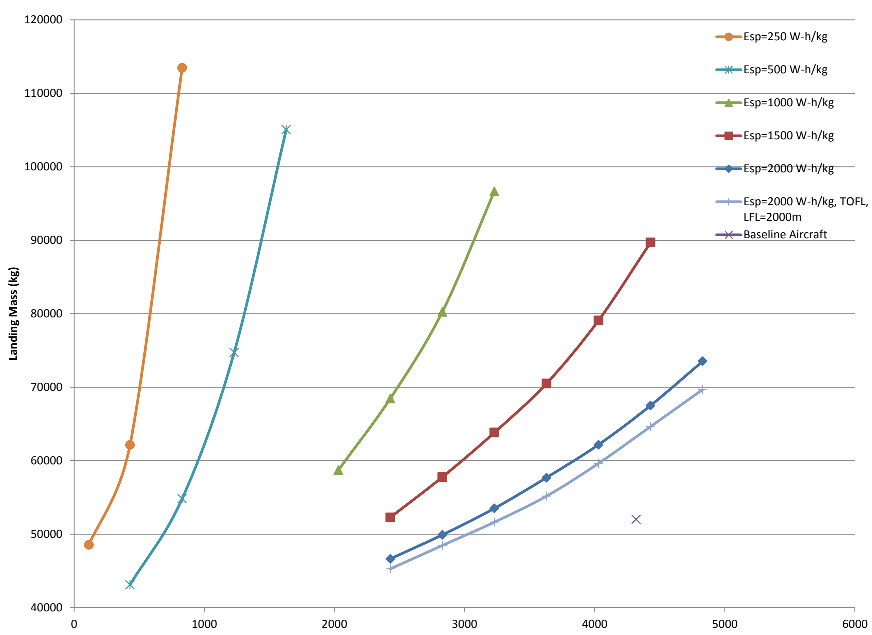


Figure 7: Battery Technology Comparison

Figure 7 illustrates that decreasing the design range of these aircraft may allow for feasible designs, even using existing (or at least near-term) battery technology. Nonetheless, one should note the substantial weight penalty associated with lower specific energy batteries. Furthermore reducing the number of passengers is recommended for these very short range aircraft (e.g. Esp=500 W-h/kg, range=430 km), and the designer would likely start with a "clean sheet" approach.

Additionally, the plot illustrates that, when the field length constraint is relaxed, some weight gains can be seen, although to a smaller extent than one might expect. In this case, the optimizer lowers the wing surface area, which decreases drag at cruise, but this is offset by the fact that the higher surface area allows for a much slower climb rate (noting that $P \propto V^3$). At longer design ranges, relaxation of this constraint achieves additional mass gains, as the climb segment becomes a smaller fraction of the overall mission.

Interestingly, as the specific energy of the battery decreases, the difference in specific energy between fully charged and discharged batteries becomes less significant, as shown in Figure 9 in the Appendix. As a result, the 250 W-h/kg designs also approximate the performance of aircraft designed using more conventional battery chemistries at that specific energy (such as state of the art lithium-ion, or lithium-sulfur batteries).

On the other hand, these aircraft configurations were designed assuming no other technology improvements, which could lead to further weight reductions if well implemented. Additional optimization while factoring in advanced technology such as laminar flow, boundary layer ingestion, and composites, should yield considerably more improvement. Figure 8 shows the effect of designing the aircraft using superconducting motors at the 4400 km range, increasing the motor efficiency from 95 % to 99 % while using the superconducting motor sizing correlation from Figure 1.

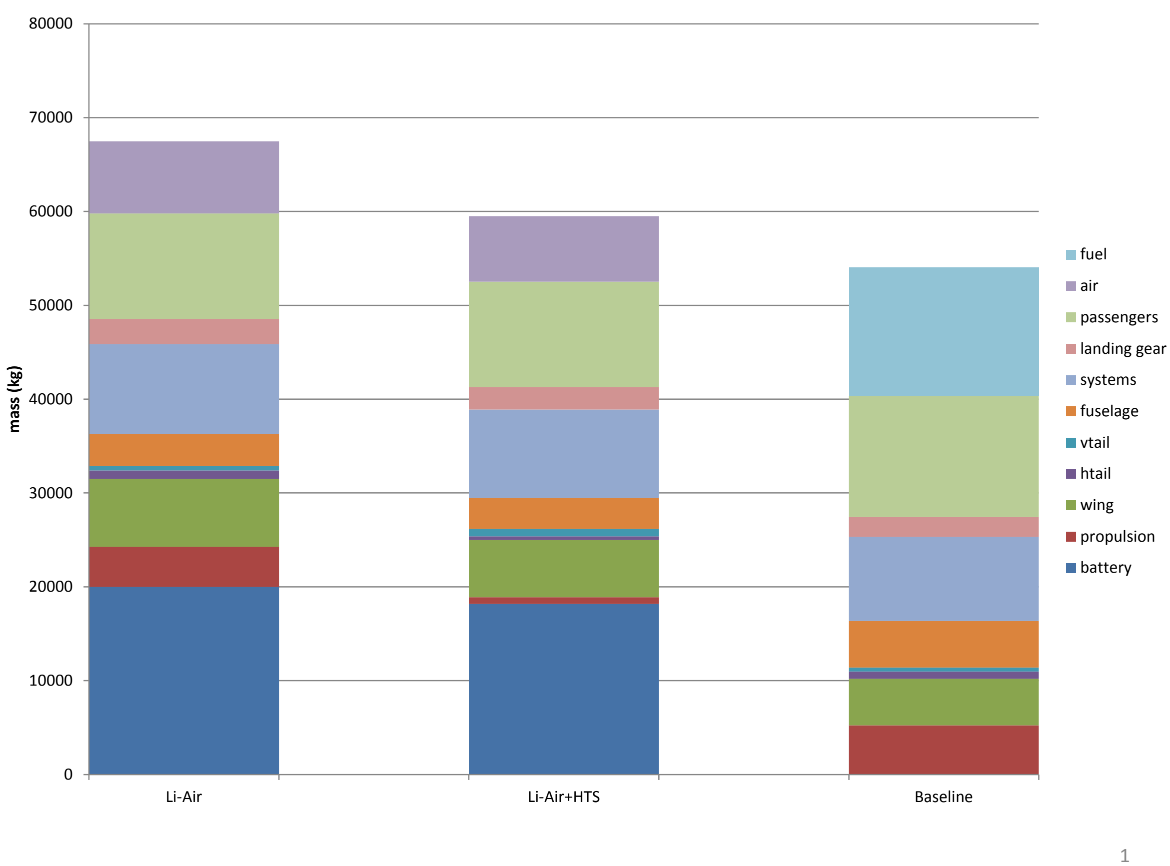


Figure 8: Electric Technology Comparison

Figure 8 compares the component weight breakdown of an air-cooled-motor based design, an HTS-motor design, as well as the baseline aircraft. This chart illustrates that substantial gains can be made in the design of these aircraft based on technology improvement Notably, the takeoff weight of the HTS design is actually lighter than the gross takeoff weight of the baseline (52,500 kg vs 54,000 kg). More aggressive configuration changes, as well as the inclusion of composites could further improve feasibility, and are worthwhile topics for follow up studies.

IV. Conclusions

Electrically-driven aircraft at the regional jet scale appear somewhat promising, at least in the initial conceptual design stages, when using these advanced batteries. Moreover, due to the fact that much of the increased demand for commercial aviation is at shorter mission ranges, lighter, shorter-range aircraft may be able to find a niche in the growing market. Furthermore, the introduction of more unconventional concepts, including blended-wing-body designs, coupled with distributed propulsion and boundary layer ingestion could result in substantial additional mass gains. However, looking forward, there are a number of questions that need to be addressed in follow-up studies to gain a more complete understanding of the feasibility of these aircraft. Firstly, analysis on the potential benefits of charging the battery directly vs. designing the battery to be easily removable and replaced with a fully charged one at the airport must be considered. Secondly, battery mass accumulation is likely to change the center of gravity of the aircraft, which could change the aerodynamic characteristics considerably, and needs to be addressed via solid geometry modeling. Thirdly, thermal losses, and their role in the overall electric system efficiency should be addressed. Finally, economic trade studies need to be undertaken to compare the costs/benefits of operating these aircraft based according to an assumed cycle-life of lithium-air batteries. Work is ongoing in refining the modules and investigating how the incorporation of additional technologies, such as distributed propulsion and boundary layer ingestion, affect the overall shape of the design.

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V. Appendix

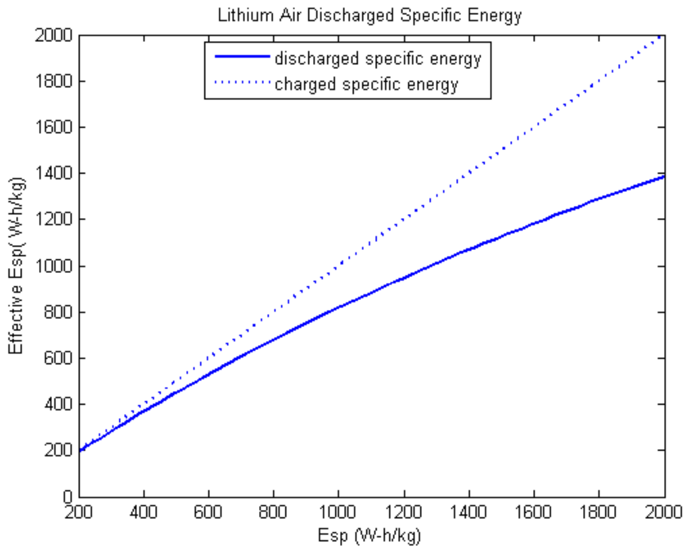

Figure 9: Lithium Air Discharged Specific Energy

Table 4: Flight and Descent Trajectories

$\dot{h}_{climb_1}$	10.16 m/s
$\dot{h}_{climb_2}$	7.62 m/s
$\dot{h}_{climb_3}$	7.62 m/s
$\dot{h}_{climb_4}$	4.572 m/s
$\dot{h}_{climb_5}$	1.016 m/s
$\dot{h}_{descent_1}$	8.128 m/s
$\dot{h}_{descent_2}$	7.62 m/s
$\dot{h}_{descent_3}$	7.62 m/s
$V_{descent_1}$	230 m/s
$V_{descent_2}$	200 m/s
$V_{descent_3}$	140 m/s

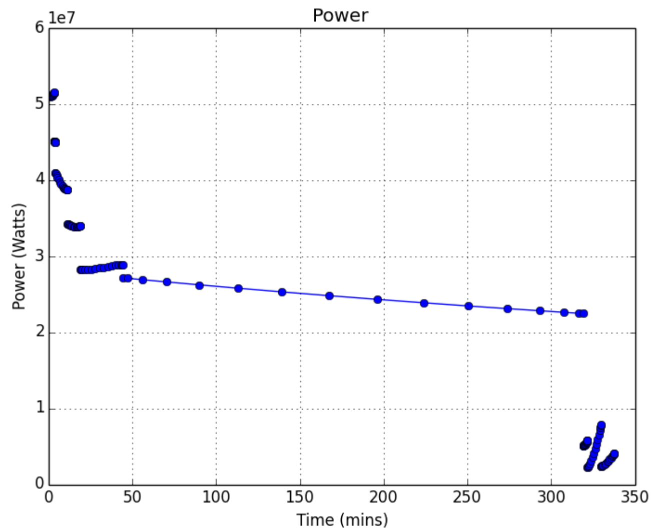

Figure 10: Baseline Power Profile

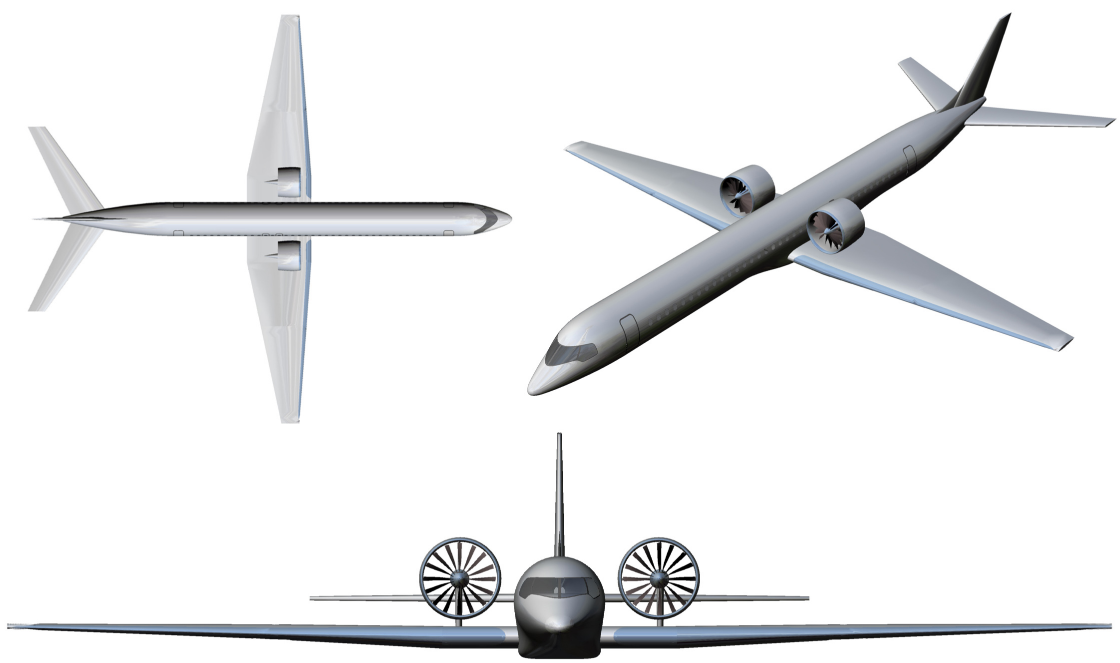

Figure 11: Aircraft Models