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Ammonia as an Aircraft Fuel: A Critical Assessment From Airport to Wake

Zero-emission aviation initiatives have mainly focused on using hydrogen or drop-in biofuels and sustainable aviation fuels (SAF) to replace fossil-based jet fuels to achieve near-term reductions in carbon emissions with minimal impacts on the global aircraft fleet and supporting infrastructure. Despite significant advances in the production of such fuels, scaling up manufacturing capability to be cost-competitive is an ongoing effort. This paper discusses ammonia as a near-zero-emission carrier of green hydrogen for aviation. Ammonia is proposed as a carrier of hydrogen fuel, a thermal sink for compressor intercooling, and cooling of cooling air, for NO_x elimination, and for condensation of water vapor to reduce contrail formation. A two-pronged investigation is presented, where first, a holistic discussion on alternative fuels identifies ammonia as a suitable hydrogen carrier for aviation. Second, the implications and potentials of ammonia are discussed and analyzed at the airframe and engine system level. Stemming from the already established fertilizer industry, a robust supply chain for ammonia exists together with experience in handling large quantities of the fluid despite its higher toxicity compared to hydrogen and other alternative aviation fuels of the future. It is found that ammonia requires significantly less water than SAF in production, on par with hydrogen, at comparable life cycle emission levels. The feasibility of heat exchangers for compressor intercooling and turbine-cooled cooling air, enabled by ammonia's non-coking properties, is demonstrated, and paves the way toward efficient zero-emission engine cores. [DOI: 10.1115/1.4062626]

Keywords: aeronautical and aerospace propulsion systems, alternative propulsion/energy storage systems, catalyst, clean energy, safety, systems engineering, transportation, turbines

Introduction

There are more than 5400 airplanes in the air during peak hours and more than 45,000 daily flights in the US, totaling more than 16

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million flights annually before 2020 based on FAA data [1]. According to the US Department of Transportation [2], the annual transportation of over 1 billion passengers generates more than 10.8 million jobs and constitutes 5.2% of the US GDP.

While the aviation industry has historically brought great value to the world, connecting countries and cultures, providing jobs and financial security to millions, and allowing for travel and leisure for billions, it currently faces a crucial crossroad. The Earth is facing an unprecedented global crisis: Arctic Sea ice down 13% per decade since 1979, global temperature is up 1.01 °C, the sea level has risen 10 cm since 1993 (exacerbating hurricane-related coastal flooding, amongst other things), and global ice sheets are down 427 billion metric tons per year since 2002. In regards to extreme weather, the number of large fires in the western United States has more than doubled from 1984 to the present, droughts have increased, and heavy precipitation events and cyclone wind intensities are expected to increase by roughly 5% and 14%, respectively, for a 2 °C global warming scenario [3–5]. As global warming heightens humanity’s awareness of its impact on the environment, collective measures are taken to reduce the impact in all sectors. Currently, aviation accounts for 2.5% of the global CO₂ emissions. However, given increased globalization and the interconnected lifestyle of people worldwide together with the ongoing development of many countries, aviation’s share of global CO₂ emissions is expected to rise to 3.5% by 2050. This rise is equivalent to roughly 1 billion metric tons of CO₂ per year despite the improved fuel efficiency of newer aircraft [6]. This emissions growth is what has been fueling the industry’s efforts to decarbonize as soon as possible. In 2009, aviation became the first industry where all major stakeholders, OEM, and airlines alike, agreed to ambitious carbon reduction goals. These goals included improving global fleet fuel efficiency by 1.5% per year from 2009 to 2020—a goal that eventually was exceeded with 2.3% annual improvements on a rolling average [7]—stabilizing emissions from 2020 onwards with carbon-neutral growth, and reducing emissions to half of 2005 levels by 2050 [8]. Meeting these ambitious goals, without substantially leaning on offsets, requires massive investment in green alternative fuels, like ammonia (NH₃), which this paper seeks to explore. Therefore, this paper approaches the topic of decarbonization of aviation on two different levels of granularity. First, the paper explores the implications of fuel selection from a top-level and holistic perspective. Second, the paper presents a technological solution on how alternative fuels could be utilized on both the airframe and engine level as these fuels present new engineering challenges, such as the sizing of additional components, integration into the

flow path, and their impact on the overall engine performance at various operational points.

Strategies for the Decarbonization of Aviation

Turbofan engines and turbine-based auxiliary power unit (APU) are the two major aircraft systems that generate emissions. The present study focuses on carbon reduction strategies related to the propulsion system. Two mitigation strategies exist for the substitution of fossil fuel-based Jet-A with (1) other energy carriers such as hydrogen or batteries, or (2) the use of carbon-neutral hydrocarbon fuels (SAFs). A comparison of the baseline Jet-A against battery-electric, H₂-fuel cell, H₂ turbine, sustainable aviation fuels (SAF), and NH₃ is given in Table 1 which is partially adapted from Ref. [9].

Any new aviation technology must address several points concurrently: (1) technical requirements, (2) safety, (3) cost and schedule for upgrading the global fleet of airplanes and airports, (4) operating cost, and (5) the global supply chain. Fuel accounts for up to 43% of an airline’s operating cost [10]. Over the past two decades, zero-emission aviation efforts have focused on using drop-in biofuels to replace fossil-based jet fuels. Drop-in biofuels are an attractive option to reduce carbon emissions since they can be incorporated into the global fleet without major aircraft or infrastructure changes being required. While significant advances have been made in the chemistry and production of such fuels, the scaling up of manufacturing capability to provide cost-competitive drop-in jet fuels for the global fleet has been a challenge [11]. Two important alternatives to hydrocarbon-based fuels are batteries and hydrogen. With an increasing share of terrestrial power generation coming from renewable sources attention has shifted toward the need for energy-dense and affordable storage of energy. In this context, electrical storage in a battery and chemical storage in the form of hydrogen (or a hydrogen carrier) are two prominent technologies. Hydrogen can be obtained by electrolyzing water, especially when the supply of electrical energy exceeds the demand. Hence, this form of hydrogen can be called e-H₂ (or electricity-derived hydrogen) and is often referred to as “green” when the source of electrical power is renewable.

While both electrical and chemical storage can be used in aviation to provide propulsive power, the required thrust-to-weight ratios limit the proposed usage of electrical batteries to small aircraft and short-duration flights [12,13]. To achieve zero-emission commercial aviation in the 2050s globally, cursory analysis suggests that e-H₂ (or an alternative hydrogen carrier as discussed in Ref. [14]) has the highest performance metrics for many mission

Table 1 Kerosene compared against battery, SAF, ammonia, and liquid hydrogen (partially adapted from Ref. [10])

Kerosene baseline	Battery-electric	H ₂ -fuel cell	H ₂ turbine	SAF	NH ₃
Climate impact (integrated)	100% reduction	75–90% reduction	50–75% reduction	30–60% reduction	50–99% reduction
NO _x only	0	0	Potential increase	Same	Almost zero
Aircraft design	Battery density limits range to 500–1000 km	Feasible only for commuter to short-range segments	Feasible for all segments except for flights >10,000 km	Only minor changes	Feasible for all segments except >8000 km
Aircraft operations	Same or shorter turnaround time; weight remains constant throughout a flight negatively impacting range	1–2 × longer refueling times for up to short-range; special safety standard	2–3 × longer refueling times for medium to long-range; special safety standard	Same turnaround times	Same or marginally longer turnaround times
Airport infrastructure	Fast-charging or battery exchange system required	LH ₂ distribution and storage with cryocooling are required; special safety precautions are necessary		Existing infrastructure can be used	Needs NH ₃ distribution and storage; no cryocooling
Global supply chain concerns	Minimal—used in other applications	Supply interruption		Quality uniformity and potential agricultural land use	Minimal—existing infrastructure (e.g., fertilizer)

Table 2 Flame characteristics of hydrogen and ammonia

Fuel	H ₂	NH ₃
Maximum laminar flame speed (cm/s)	291	7
Adiabatic flame temperature (K)	2400	2075
Flammability range	0.1–7.1	0.6–1.4
Critical temperature (K) and pressure (MPa)	33 and 13	405 and 11.3
Triple point temperature (K) and pressure (MPa)	14 and 0.07	195 and 0.006

flight profiles among fuel candidates which have been investigated [9,15–18]. Hydrogen has an unmatched gravimetric energy density (LHV) of 120 MJ/kg, which is much higher than 43–46 MJ/kg for kerosene. However, liquid hydrogen storage comes with complexities [19–21], and its volumetric energy density of 8.5 GJ/m³ is far lower than 35–38 GJ/m³ for kerosene. Owing to its low volumetric energy density, hydrogen needs to be stored as a cryogenic liquid at 20 K (–253 °C) or as a gas at high pressure (~700 bar) which could add weight to an aircraft and potentially reduce range or passenger capacity. Either of these onboard hydrogen storage alternatives comes with challenges for the commercial air transportation sector [22–24]. Furthermore, cryogenic storage schemes must account for thermal shock during refueling to preserve fuel system durability. The higher flame temperatures in hydrogen combustion (Table 2) have the potential for increased NO_x emissions and higher amounts of water vapor in the exhaust, relative to carbon-containing fuels, which may represent a challenge to meeting emissions expectations and lead to increased contrail formation, respectively [25]. In other words, while e-H₂ has many favorable attributes as a zero-carbon aviation fuel, it presents unique handling and safety challenges, and requires innovation to address all forms of emissions. However, e-H₂ can be used in the synthesis of another molecule [26] with less onerous handling requirements, not requiring cryogenic liquefaction or high-pressure storage. In this context, ammonia [27] is an excellent H₂-carrier, which can be catalytically cracked [28,29] to provide H₂ gas before combustion and may afford paths to reduce overall emissions.

The Case for Ammonia. For ammonia to be a viable decarbonized energy carrier for aviation, it must meet the minimum requirements for aviation fuel from an aircraft platform integration standpoint, and it must be scalable, affordable, safe, and with low resource consumption. These broader points are discussed in the following sections, followed by a system-level analysis in the subsequent sections.

General Considerations. NH₃ remains in a liquid state over a much wider temperature range than hydrogen, and has a robust

and mature supply chain. Relevant property comparisons are listed in Table 3. Ammonia, acting as a hydrogen carrier, offers superior endothermic fuel characteristics [28,29] over kerosene because it is stored as a liquid at 240 K (–33 °C) and ambient pressure, it absorbs significant energy when releasing H₂ upon cracking, and does not form coke. Direct combustion of ammonia reduces the amount of thermal sink available by the fuel, relative to a cracking approach.

Interestingly, liquid ammonia carries more hydrogen per unit volume than liquid hydrogen itself, thus providing benefits for storage within the wings of future aircraft. Hence, a concept such as depicted in Fig. 1 could be envisioned where overall airplane performance is augmented by the use of a supercritical carbon dioxide (sCO₂) power cycle to convert core exhaust heat into electricity for onboard uses [30]. The sCO₂ power systems are a promising technology for the recovery of waste heat in the exhaust flow of the engine [30–32]. This sCO₂ subsystem could play an important role in offsetting the impact of ammonia’s LHV of 18.6 MJ/kg (figure taken from Table 3).

Infrastructure, Supply, and Safety. Aviation is a global industry and hence there needs to be a global supply chain for whatever fuels are adopted by the industry. This is where ammonia may have advantages over both e-H₂ and SAF. Ammonia has a robust supply chain around the globe [33,34], particularly because of its use in fertilizers and as a chemical feedstock for many applications. In the US alone, there are 32 ammonia plants in 17 states and over 1900 miles of ammonia pipeline [35]. By contrast, in 2022, hydrogen infrastructure is primarily limited to the Space Coast in FL and the Gulf Coast, although significant expenditures are being made to expand that infrastructure in the coming decade through infrastructure development efforts such as hydrogen hubs and large-scale hydrogen utilities.

The infrastructure gap is compounded by the current production rates of ammonia and jet fuel. While future production estimates of all alternative fuels include significant increases, in 2020 worldwide, 196 million tons of ammonia were produced [33], versus 87 million tons of hydrogen [36] and only 0.18 million tons of SAF production capacity [37]. Today, only ammonia’s production volume by mass is comparable to the level of jet fuel consumed globally, which peaked at 344 million tons in 2019 [38]. The US EIA further expects increases in traffic growth to cause jet-fuel consumption to grow to 574 million tons of fuel by 2050 (corresponding to an energy equivalent of 24.8 EJ as shown in Fig. 2) which means a total of 230 million tons of fuel (9.9 EJ) would need to be offset by either alternative sustainable fuels or carbon offsets [38]. As an example, shown in Fig. 3, the RefuelEU mandates specify SAF blending requirements for EU member states, and based on several SAF production estimates and their trends, there is a clear issue meeting the mandates. With several production estimates for SAF ranging between 2% and 6% in 2030, the 2030 mandate of 5% SAF blending may work, but the trends require a

Table 3 Comparison of ammonia with kerosene, hydrogen, and methanol

Properties	Unit	Kerosene	Hydrogen	Methanol	Ammonia
Stored as	—	Liquid	Gas	Liquid	Liquid
Temperature	°C	Ambient	Ambient	–252.9	–33 (or 25)
Pressure	MPa		70	Ambient	0.1 (or 0.99)
Density	kg/m ³	840	42	70.8	600
Explosive limit	%vol	0.7–5	4–75	4–75	6.7–36
LHV	MJ/kg	43–46	120	120	20.1
	MJ/l	35–38	4.5	8.49	15.8
H ₂ content	wt%	N/A	100	100	12.5
	kg-H ₂ /m ³	N/A	42.2	70.8	99
Hydrogen release	—	N/A	Pressure release	Evaporation	Catalytic Decomp. @ Temp.
					>200 °C
Energy to extract H ₂ (g)	kJ/mol-H ₂	N/A	—	0.907	>300 °C
					16.3
					30.6

Note: Data based on Ref. [25].

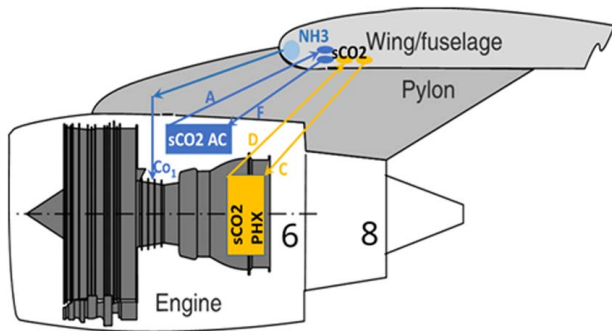


Fig. 1 Proposed engine suspension under the wing with ammonia fuel and WHR connections

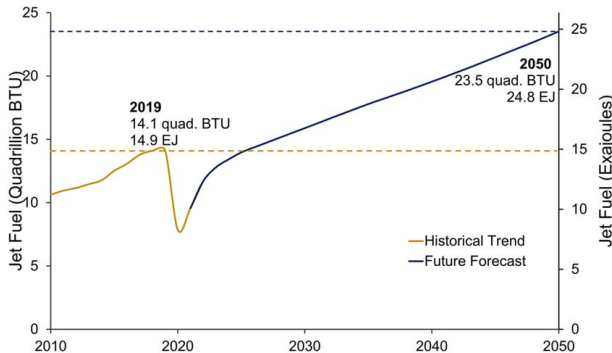


Fig. 2 Historical and forecasted global jet-fuel consumption according to Ref. [38]

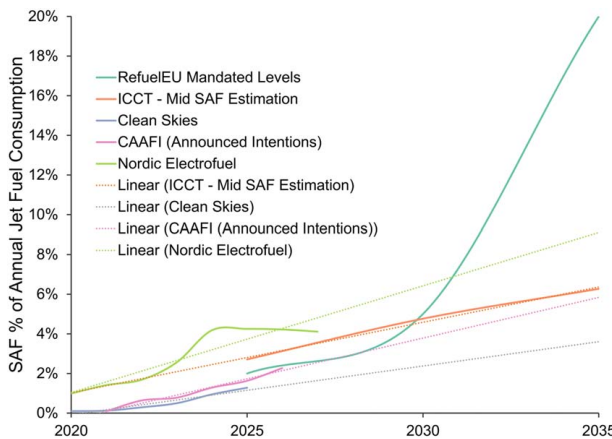


Fig. 3 Forecasted SAF fraction of annual jet-fuel consumption based on publicly available data [9,39–42]

significant upward disruption to meet the jump to 20% SAF blending in 2035 [9,39–42] (for those SAFs where the feedstocks are fats, oils, and greases versus power-to-liquid schemes which leverage CO₂ or other non-triglyceride pathways). The possible lack of SAF production and feedstock availability is a challenge that ammonia may have an easier time solving.

Many countries in developing and under-developed parts of the world do not have the infrastructure for safe and reliable hydrogen storage and fueling. Hydrogen has a high flame speed and is a flammable gas according to NFPA classification with an NFPA 704 rating of 4 [43,44] whereas methane and kerosene have flammability ratings of 4 and 2, respectively. This difference in reactivity must be appropriately managed for the safety-conscious aviation industry. Difficulties in the safe and easy handling of hydrogen have limited its widespread usage outside of the space and chemical industries [45]. This raises challenges around the

feasibility and practicality of a global infrastructure and supply chain for refueling airplanes worldwide with liquid hydrogen [46,47]. At the same time, ammonia is also treated as a flammable gas according to NFPA classification, however, at a low value of one. Furthermore, anhydrous ammonia's hazard classification is "corrosive and poisonous gas." Concentrations of 300 ppm are considered immediately dangerous to life or health (IDLH) due to their high acute inhalation toxicity in humans [48]; however, ammonia is detectable by smell already at concentrations below harmful limits [49]. In contrast, no IDLH limits are defined for kerosene. Kerosene and ammonia are both considered marine toxins with long-lasting effects. Although ammonia is toxic, it is widely used in the chemical and fertilizer industry. Accordingly, multiple safety codes, handling, and transportation procedures have been developed over time and might be developed for aviation as well. Discussions around novel potential aviation fuels such as e-methane, hydrogen, and ammonia always must include the aspects of safety. It appears that it eventually comes down to the strategies of mitigating the risks of flammable and explosive fuels (hydrogen and methane) on the one hand and toxic fuels (ammonia) on the other hand [45].

On the contrary, bio-derived SAF [50] can provide the easiest route to decarbonized aviation based on net-zero-carbon emission (when renewable energy is used from the entire field-to-wake lifecycle). As SAF [51] is a drop-in replacement, airplanes and supporting infrastructure do not require upgrades, thus avoiding tremendous global investment. However, there are certain challenges with SAF as well. First, slight changes in SAF's chemistry, because of variation in source, can affect secondary or tertiary characteristics. For example, change in aromatics can affect seal swell, leading to potential leakage [51–53]. Second, despite recent advances in combustor design technology, reduction of NO_x to single-digit-ppm is challenging for jet engines. Adverse environmental effects besides NO_x, such as contrail formation, may be under increased scrutiny in the future [54,55]. And last—for SAFs that come from sugar and starch feedstock, fats, oils, and greases—any competition with the global food supply may be subjected to future societal, ethical, and policy restrictions, which will then motivate a search for alternatives to SAF.

In summary, an argument has been made above in favor of exploring ammonia as a hydrogen carrier to store, transport, and manage heat, while the hydrogen generated from that ammonia is used as a carbon-free fuel. Building on that, this paper offers an alternative perspective for a scalable pathway to zero-emission aviation using electricity-derived (or green) ammonia as a hydrogen carrier. A holistic approach is chosen which includes airport storage, fueling, and eventually flight: from airport to wake.

Lifecycle Considerations. When discussing ammonia's viability as an alternative energy source for aviation, it is worth noting the lifecycle differences between traditional kerosene Jet-A, sustainable aviation fuels, hydrogen, and ammonia. Even though ammonia and hydrogen produce no CO₂ upon combustion, CO₂ and other greenhouse gases are produced throughout various parts of the lifecycle. Therefore, it is important to note the total lifecycle carbon equivalent emissions (as well as energy usage and water consumption) to ensure the lifecycle viability of ammonia as a transport fuel.

Using GREET2020 and a variety of sources from Argonne National Labs, NREL, and others, lifecycle resource and emission simulations can be built of the fuel pathways to get the lifecycle metrics of jet-fuel, ammonia, hydrogen, and their green alternatives for comparison [56–62]. It was decided to use ethanol-to-jet SAF (ETJ) from cellulosic biomass (corn stover) as a SAF representative since corn stover is the most readily available and economically viable biomass in the US [63,64]. For LH₂ and LNH₃, a future renewable energy grid of 50% solar and 50% wind is used. It is worth noting that there are many other alternative aviation fuels (FT-DAC, FT-BIO, RNG, SNG, etc.) that would be good for comparison, and this is just a small subset of relevant fuels.

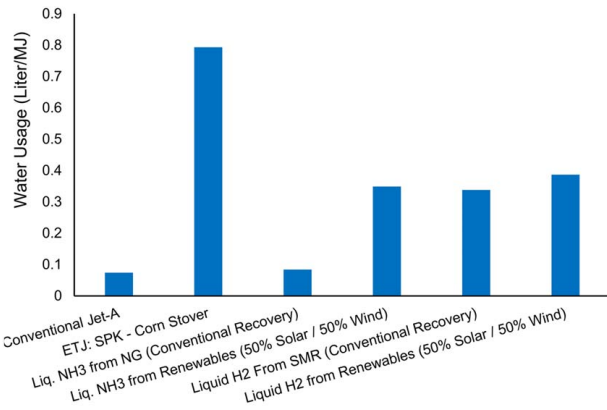


Fig. 4 Water consumption potential by fuel

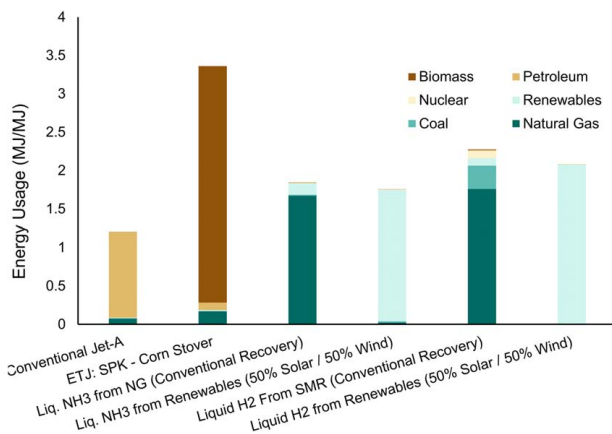


Fig. 5 Energy resource consumption by fuel

Conventional Jet-A has the lowest amount of water consumption potential (WCP) as shown in Fig. 4. There is high water usage involved in ETJ (0.8 l/MJ) since most biomasses require water to grow. Additionally, high water consumption is required for hydrogen electrolysis, steam methane reformation, and the production of grid energy used for liquefaction of hydrogen. All Jet-A alternatives have higher WCP, and renewable liquid ammonia is comparable to green LH₂ and about 55% the WCP of ETJ, if freshwater is not a constraint. NH₃ is preferable or comparable to crop biomasses and renewable hydrogen from electrolysis.

Figure 5 shows the energy resource consumption in megaJoule that is required to produce 1 MJ of fuel. Conventional Jet-A is, once again, the most preferable option in regard to absolute energy usage (1.21 MJ/MJ). This is due to the fact that refining crude oil into jet fuel is not energy intensive compared to reference fuels. In a similar trend to water usage, liquid NH₃ is comparable to liquid H₂ (1.8 MJ/MJ versus 2.1 MJ/MJ) and significantly lower than ETJ—Corn Stover (3.3 MJ/MJ fuel). In other words, whereas 3.3 units of energy are required to produce 1 unit energy of useable ETJ fuel, liquid hydrogen and ammonia require about twice their heating values as energy input. It is apparent that the energy input composition at the front end is strongly dependent whether ammonia and hydrogen are produced from fossil fuels (natural gas or SMR) or renewable energy sources. This is a positive indication that green ammonia can do well in a green energy-constrained market.

The third major key environmental performance metric for these fuels is the global warming potential or emission potential integrated over 100 years relative to CO₂ gwp100, or the lifecycle CO_{2eq,100} emissions per megaJoule of fuel, respectively;

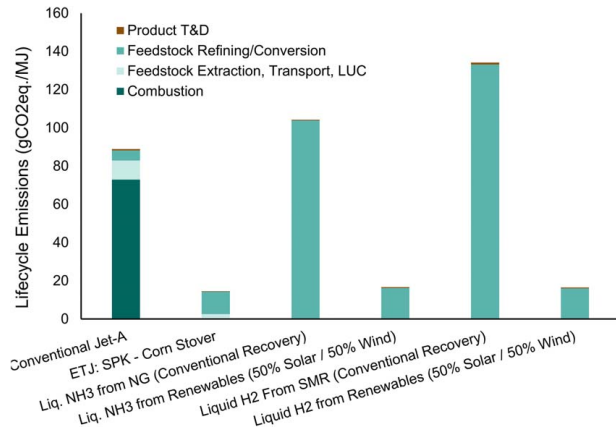


Fig. 6 Emissions (GWP100) by fuel

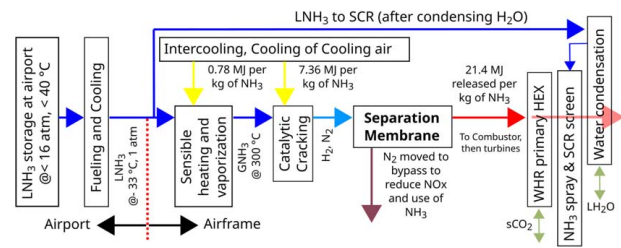


Fig. 7 NH₃ flow path from airport fuel storage to engine wake. The cracking temperature of 300 °C, as shown here, is only for illustration.

comparatively shown in Fig. 6. The standard for jet fuel, adopted by ICAO and used in CORSIA CO_{2eq}/MJ [65–67]. Today’s ammonia and hydrogen production, sourcing hydrogen from natural gas, is worse than conventional Jet-A production 104 and 134 gCO_{2eq}/MJ, respectively. However, the sustainable future alternatives, ETJ-SAF, green ammonia, and green hydrogen are all very comparable (15, 17, 17 gCO_{2eq}/MJ respectively) and are all an 80% reduction in gCO_{2eq} emissions over today’s fossil sourced Jet-A fuel. Any of these alternatives show the promise to nearly decarbonize aviation, and when combined with offsets, fleet improvements, and operational and infrastructure improvements, form a complete strategy for reaching the industry’s 2050 carbon reduction goals.

With “green” liquid ammonia having comparable or more desirable water consumption potential, energy usage, and global warming potential to ETJ-SAF and green liquid hydrogen, two of the more popular alternative energy carriers discussed in the aviation industry, the green ammonia ranks highly when comparing metrics associated with lifecycle viability. With this in mind, it is important to conclude that the actual future viability of green ammonia and whether it’s a preferable aviation fuel comes down to the improvement of global energy grids’ carbon intensities, the availability of infrastructure for transportation and distribution, the safety in handling, the ability to produce it at scale, and airport platform considerations (some of which have been previously discussed), amongst other things. Overall, ammonia’s characteristics merit a deeper dive into its potential as an aviation fuel.

Problem Definition and Methodology. The second objective of the study is to provide an overview of energetics from ground storage to the wake of the engine and study the feasibility of an ammonia fuel system at the aircraft level. Next, the focus is narrowed down to the engine and operational level for a reference airframe and engine. The resulting engine concept from ground to wake is introduced in Fig. 7 and analyzed component by

Table 4 Engine performance parameters—Cases 1–6 ranging over the corresponding modes ground, cruise, landing, and take-off

Operation mode	(1)	(1)	(1)	(3) and (4)	(3) and (4)	(2)	—
Case	A	B	C	D	E	F	—
Altitude	0	0	0	1668	9668	10,668	m
	0	0	0	5472.44	31,719.2	35,000	ft
Ambient temperature	320	310	288.1	277.31	225.31	218.81	K
Mach number	0	0	0	0.3	0.5	0.74	—
Fuel flow	1.1	1.13	1.21	1.04	0.48	0.47	kg/s
SFC	10.24×10^{-6}	10.11×10^{-6}	9.89×10^{-6}	13.65×10^{-6}	15.04×10^{-6}	17.32×10^{-6}	kg/s(fuel)/N
Point 5							
T5	826.3	808.6	773.43	740.74	670.34	635.71	K
P5	135.6	137.64	143.16	114.6	44.41	36.52	kPa
Mass flowrate	59.25	61.69	67.77	59.95	28.56	28.4	kg/s
Point 2							
T2	364.52	354.48	332.82	320.39	268.89	258.98	K
P2	154.2	156.1	160.67	131.34	47.9	40.35	kPa
Mass flowrate	389.95	403.14	434.84	389.26	175.19	177	kg/s
Point 2.5							
T2.5	422.87	412.91	391.52	378.89	325.69	313.11	K
P2.5	247.63	253.98	269.08	223.72	86.62	72.64	kPa
Mass flowrate	59.33	61.78	67.91	60.11	28.65	28.49	kg/s
Point 3							
T3	856.98	840.73	806.97	779.03	697.6	661.32	K
P3	2663.49	2751.10	2974.54	2448.84	1020.90	834.16	kPa
Mass flowrate	48.43	50.44	55.45	49.07	23.39	23.26	kg/s
Point 4							
T4	1618.9	1592.5	1542.5	1521.2	1441.6	1338	K
P4	2305.18	2381.4	2576.17	2305.34	967.43	795.54	kPa
Mass flowrate	49.54	51.57	56.65	50.11	23.87	23.73	kg/s

Table 5 Fundamental engine parameters

Parameter	Value
Model	CFM56-5B2
Type	High-bypass ratio turbo fan engine
Bypass ratio	5.2:1
Thrust (SI)	27,236 N @ 10,668 m
Thrust (imperial)	6123 lbf @ 35,000 ft
Mach number	0.74
Overall pressure ratio	35.496
Fan pressure ratio	1.7
Maximum cycle temperature	1619 K

component. This encompasses six different operational cases ranging from ground operations to cruise, as shown in Table 4. The data are created based on a code which replicates the jet engine's operational characteristics. The code was previously verified with experimental data from different engine configurations [68–70]. The engine's key parameters are listed in Table 5. The underlying code is written in FORTRAN language and consists of major components represented by blocks with the fundamental conservation principles of mass, momentum, and energy. The code uses operation maps for the compressor, turbine, and combustor and allows for steady-state and transient operation with fixed and variable geometry [68–70]. In the next step, the primary and recuperative heat exchangers are sized based on the energetic cycle calculations. The objective is to investigate the feasibility of the proposed design alterations from a geometric and system design point of view.

Results and Discussions

Aircraft Platform Considerations. As previously alluded to, transitioning the current aircraft fleet to different energy sources—SAF, liquid hydrogen, and liquid ammonia—requires varying

amounts of effort to make the aircraft platform technologically feasible.

To incorporate SAF, a key aircraft platform difference is the use of nitrile O-rings in some aircraft fuel systems. Past fuel systems and test platforms have shown that O-rings in the fuel system experience differences in swelling and tensile strength changes due to exposure to different types and quantities of aromatics in the fuel. Once nitrile O-rings are exposed to reasonable quantities of aromatics and undergo swelling [71], aromatics are permanently required in future fuels to maintain satisfactory seal-swelling volumes. In a future scenario where fuel systems may alternate between aromatic and paraffinic sustainable aviation fuels, alternative O-ring materials may be required to prevent issues in the fuel system, but further testing is required to validate this.

For any proposed hydrogen aircraft, system-level design choices will be required. The aircraft systems need to handle cryogenic fuel (-252.9°C , 20 K) as well as its phase transition from liquid to gas. To properly combust the fuel and meet engine restart requirements as required by the FAA, modifications may also be needed for key components, such as fuel injectors, igniters, and combustors. These propulsion components may need to be modified even further if NO_x from hydrogen based fuels is as much an issue as some sources predict [72]. Hydrogen fuel also requires a novel fuel system to handle cryogenic temperatures and properly distribute and condition the fuel for the propulsion system. The fuel system may also need to be able to vent boil-off hydrogen through pressure release or recover the boil-off and re-liquefy it for later combustion. Large hydrogen storage tanks with space for crumple zones around them may need to be sized to handle the fuel (which may no longer be stored in the wings), and these would take up large amounts of space in the fuselage which may need to be stretched to include the space for the tanks. The aircraft's wings may need to be redesigned both as a consequence of the potential landing gear growth due to fuselage changes and also because the wings may no longer be storing fuel. It is also currently unclear to what degree hydrogen aircraft will be creating persistent contrails compared to kerosene fueled aircraft, and additional considerations may need

to be taken for active contrail avoidance (e.g., routing changes, pre-flight contrail prediction, etc.) if hydrogen-based fuels (H_2 , NH_3 , etc.) end up causing more contrails than hydrocarbon fuels.

While SAF platform integration takes minimal effort, and hydrogen integration looks more like a total redesign, ammonia integration would lie in the middle. Akin to hydrogen, a novel fuel system (discussed here) would be needed to ensure the ammonia is properly conditioned and distributed, and changes to the propulsor would be required to ensure combustion of the fuel (and possible NO_x reductions). In regard to storage, ammonia can be stored in the wing and wing center carry-through section of the aircraft, a large benefit over pure hydrogen, but due to the decrease in LHV and density of ammonia, additional fuel bladders and storage space may be needed in other areas of the aircraft to compensate. It is unclear whether major fuselage modifications and therefore landing gear changes would be required to handle this increase in fuel volume. Ammonia also faces the same issue (or benefit) with contrail avoidance as hydrogen.

Selection of Reference Engine and Airframe. A reference aircraft and fuel system was selected to serve as a basis of comparison for zero-emission platforms evaluated in this study. Narrowbody passenger aircraft are used for more than 60% of all passenger flights and fly more than 50% of all revenue passenger miles thus accounting for a larger proportion of CO_2 emissions in aviation [73] than widebody aircraft. Market forecasts through 2040 [18] show that narrowbody aircraft deliveries are projected to outpace widebody by a factor of 4.25. These trends, and the increasing use of narrowbody platforms for long-haul flights, make a state-of-the-art narrowbody aircraft the appropriate choice for the reference aircraft for which the decarbonization potential is the largest. As such, a Boeing 737-8 (737 MAX 8), which accounts for nearly 50% of 737 MAX sales and is powered by the CFM LEAP-1B high-bypass ratio turbofan engine, has been selected as the reference aircraft for this study. A Boeing 737 MAX 8 seats up to 220 passengers (typically 178–193 in a two-class cabin) and has a rated range of 3550 nautical miles (6575 km).

SAF, as defined by the International Air Transport Association (IATA) [74], is the fuel selected for the baseline aircraft in this study. This selection is reinforced by Boeing's plans [17] for all of its aircraft to be certified to operate on SAF by 2030 and the importance of SAF in meeting Boeing's goal of reducing aviation CO_2 emissions by 50% (relative to 2005) by 2050.

The engine model is based on a high-bypass ratio turbofan engine (most of the air bypasses the core of the engine and is exhausted out of the fan nozzle) with a bypass ratio of 5.2:1, generating 27,236 N (6123 lbf) of thrust at 10,668 m (35,000 ft) and a Mach number 0.74. The engine is a two-shaft (or two-spool) engine, where each shaft is powered by its own turbine section (the high-pressure and low-pressure turbines, respectively). The fan and booster (commonly called the low-pressure compressor (LPC)) are mounted on the low-pressure shaft. The overall pressure ratio is 35.5 and the fan pressure ratio is 1.7. The maximum cycle temperature is 1619 K. A schematic of the engine is shown in Fig. 8. The engine and engine performance parameters are closely modeled after the CFM56-5B2 engine with openly available data [68,69], see Tables 4 and 5, the predecessor of the CFM LEAP-1B.

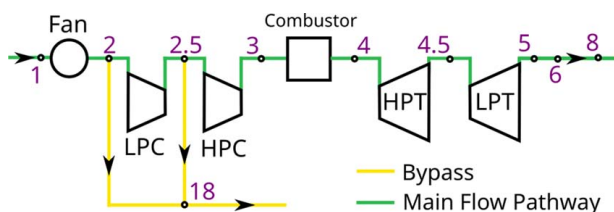


Fig. 8 Schematic of the engine

Four engine operating points were studied, namely (1) ground, (2) cruise, (3) landing, and (4) take-off, to simulate various fuel operating parameters and the various stages of a flight mission. Six cases are derived from the operational modes: Mode (1), ground, is split into three cases A–C corresponding to varying ambient temperatures at the ground simulating warmer and colder conditions corresponding to seasonal changes in temperature. Cases D and E are for landing mode (3) and take-off mode (4), and finally case F is for cruise mode (2). The parameters for each regime are listed in Table 4 and the T-s diagram of the engine for the ground mode is shown in Fig. 9. The fuel flow mass flowrates, temperatures, and pressures at the cycle points 5, 2, 2.5, and 3 are particularly important for dimensioning the heat exchangers for integration in the flow path as shown in Figs. 7 and 10, respectively. It is apparent from Table 4 that depending on the operational regime of the engine (cases A–F), the fuel flowrate and the temperatures and pressures at points 5, 2, 2.5, and 3 vary significantly. The cooled cooling air (CCA) and intercooling heat exchanger systems have to function across the entire spectrum of operational points as described in Table 4. The aforementioned repurposing of the engine and the addition of components as described in Fig. 7 require a corresponding adaption of the engine schematics which is shown in Figs. 8 and 10. Most noticeable are the LNH_3 storage tank (Co1), catalytic cracking unit (Co2–Co3), a primary heat exchanger (PHX) between points 13 and 14, and the connected waste heat recovery (WHR) unit. LNH_3 is used to intercool between the LPC and HPC by evaporating LNH_3 to GNH_3 between points Co1 and Co2. Another exchange of heat occurs between Co2 and Co3 as the catalytic cracking of GNH_3 to GH_2 is endothermic. The endothermic cracking reaction is used as a heat sink to cool air from the HPC for the HPT, thereby also enabling better turbine blade cooling performance. The bypass line, from point 2 (Fig. 10), is the air that bypasses the core as it is extracted after the fan. The bypass air's purpose is to provide a heat sink for a potential WHR unit which will be designed based on a sCO_2 closed power cycle [30–32]. The heat for the unit is transferred through the PHX, which is located after the LPT, Fig. 10. The WHR unit has the potential to generate electric power, that can support the APUs (in-cruise mode) or replace the engine-mounted generators [30,75,76].

Systems Modifications Enabled by Ammonia. One major difference between ammonia and hydrogen is the higher temperature at which it goes into the liquid phase (boiling point) at standard atmospheric pressure, i.e., $-33^\circ C$ (240 K) compared to hydrogen at $-252.9^\circ C$ (20 K), respectively. Consequently, the cooling and insulation requirement is reduced which results in less weight and reduced cooling power during flight. In-cruise cryocooling for ammonia is not required as it remains in a liquid state above 25,000 ft altitude due to the low ambient temperature in the atmosphere with increasing height as shown in Fig. 11.

Another unique characteristic of NH_3 can be exploited for multiple system-wide performance improvements. As shown in Fig. 7, NH_3 is not just used for hydrogen generation. Further, it is used for (a) intercooling [77–79], (b) cooling of air used for turbine cooling [80,81], (c) elimination of NO_x from the exhaust, and (d) condensing water from the core exhaust to limit contrail formation [55,82,83]. These features are enabled by the non-coking properties of NH_3 (as opposed to Jet-A or SAF) [51,74,84], the ability of NH_3 to reduce NO_x to N_2 in the presence of a selective catalyst [33,85,86] (again, as opposed to both Jet-A and H_2), and its low explosion potential [54,87,88]. The design challenges and opportunities are discussed one by one including a preliminary sizing of the additional components.

Intercooling. Ammonia does not coke like kerosene when used as a heat transfer medium or as a heat sink. As a result, stored liquid ammonia can be used for various thermal management duties, such as compressor intercooling, cooling of CCA [89],

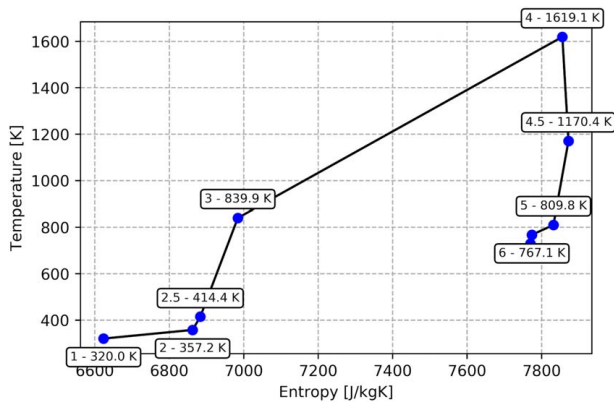


Fig. 9 T-s diagram of the engine in ground mode

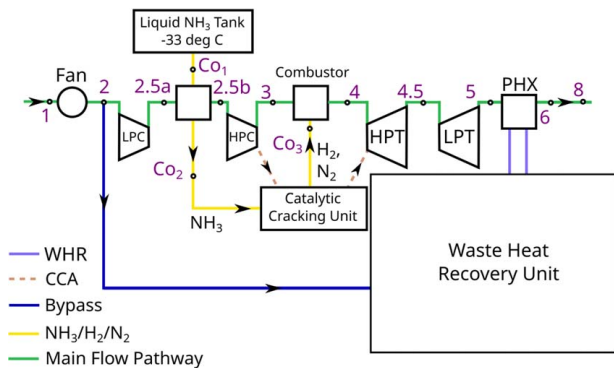


Fig. 10 Schematic diagram of the engine adapted for ammonia

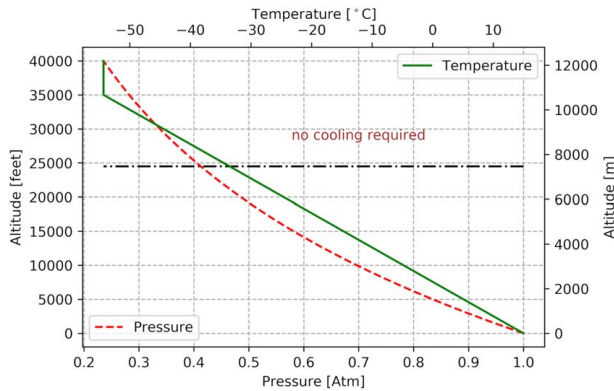


Fig. 11 Varying temperature and pressure across the atmosphere according to the 1962 US Standard Atmosphere at 15 °C and 0% humidity

and cooling of aviation electronics, which significantly improves core efficiency and specific fuel consumption (SFC) and/or minimizes extraction of power and compressed air from the core for non-propulsion purposes. Thermal management is more complex and burdensome with kerosene (or e-ethanol or e-methanol) because of its coking potential and thermal degradation limits, nor accomplished easily with hydrogen because of its leakage and flammability potential. Nevertheless, kerosene has been used for system cooling applications; e.g., in regenerative cycles. In fact, improved core efficiency as noted here can partially negate the lower gravimetric energy density of ammonia.

The use of NH_3 for intercooling between the LPC and HPC (Fig. 10) can reduce the power consumed by the HPC, thus improving overall core efficiency. A low level of continuous intercooling

can also be added by cooling the stationary casing, with an additional reduction in compressor work.

A significant fraction ($\sim 20\%$ or higher) [90] of air is extracted from the compressor as TCLA. If the extracted air is first cooled using NH_3 , as indicated in Fig. 7, then the overall cooling potential is increased, leading to a lower coolant mass flowrate [91–93], and higher core efficiency. This CCA concept is not new [94–96]. CCA can be implemented here because NH_3 is an endothermic fuel that does not coke. These contributive increases to core efficiency offset the increased system weight arising from the lower energy density of LNH_3 .

Another emission is water vapor from H_2 combustion, potentially leading to contrail formation [82,83]. However, since H_2 combustion does not create soot particles that could act as nucleation sites for condensation/ice-formation, contrails might be reduced whereas higher water content in the exhaust gases of hydrogen-burning engines may promote the formation of contrails. The uncertainty in predicting the formation of contrails by hydrogen-burning turbofan engines is high due to limited available data on that matter [97]. In addition, the NH_3 needed for selective catalytic reduction (SCR) can be routed, while still in a liquid state at approximately -33°C , through a heat exchanger (Figs. 7 and 10) to condense water out of the exhaust stream, thus reducing water vapor partial pressure and minimizing contrail formation.

The merits of intercooling warrant further investigation including an assessment of aircraft and engine integration and a tradeoff analysis between weight and pressure drop versus heat transfer. The intercooling unit would add weight to the engine, which in turn increases SFC and cost per passenger mile. Furthermore, incorporating another engine system introduces new failure mechanisms and maintenance requirements.

Catalytic Decomposition of Ammonia Into Hydrogen. Catalytic cracking of ammonia has wide ranges of efficiency based on the catalyst, the amount of catalyst, the NH_3 flowrates, and the temperature and pressure of the cracker. Ruthenium is shown to be the most active catalyst [98]. However, this comes with the greatest cost, so other cheaper catalysts have also been studied. Other catalysts based on Ni and Fe reduce costs, but also reduce catalytic activity, requiring an increase in temperature to compensate—which are higher than the temperature levels at the high-pressure compressor exit.

The Haber–Bosch process uses an iron-based catalyst to produce ammonia from nitrogen and hydrogen. This reaction is reversible, and the catalyst composition must be tailored to improve ammonia yields. This catalytic decomposition reaction occurs in the catalytic cracking unit depicted in Figs. 7 and 10. Poor iron-based Haber–Bosch catalysts will allow the realization of the reverse reaction. Previous work in this area by Tucker et al. [28] has shown that high surface area iron particles supported on a silicate matrix have good hydrogen yields from ammonia. The surface area and the support for the iron greatly affect the efficiency of this process. It was shown that the common mineral olivine (Mg^{2+} , Fe^{2+}) $_2\text{SiO}_4$ could be reduced to produce 10–50 nm diameter iron nanoparticles on a forsterite (Mg_2SiO_4) surface. This composition displayed strong catalytic activity not seen in powders without Fe nanoparticles with a rapid decomposition of NH_3 to hydrogen and nitrogen observed. The energetics of catalytic decomposition of ammonia into hydrogen is comprehensively described in Dincer [99].

The current literature suggests that ammonia will not need to be cracked at such high efficiencies for good combustion and low emissions. One study stated 10 wt% H_2 is needed for good combustion efficiency, which correlates to an ammonia conversion rate of less than 50% [100]. This lower required efficiency could allow temperatures to be lower and between 573 K and 673 K for non-Ru-based catalysts in contrast to the higher temperatures of 773 K and 873 K needed for $>96\%$ non-Ru-based cracking [101]. Extensive research has been published on adjusting temperatures, pressures, catalysts, supportors, and promoters to achieve various

Table 6 Intercooler operating conditions

Case	A	B	C	D	E	F
Altitude (km)	0	0	0	1.7	9.7	10.7
Mach (-)	0	0	0	0.3	0.5	0.74
Core flow (air)	Inlet P (kPa)	247.6	254	269.1	223.7	72.6
	Inlet T (K)	422.9	412.9	391.5	378.9	313.1
	Max flow (kg/s)	59.3	61.2	67.9	60.1	28.5
Fuel flow (NH ₃)	Inlet P (kPa)	101.3	101.3	101.3	101.3	101.3
	Inlet T (K)	240.2	240.2	240.2	240.2	240.2
	Flow (kg/s)	1.1	1.13	1.2	1.04	0.48

ammonia conversion efficiencies, which will be very helpful for onboard cracker designing [102].

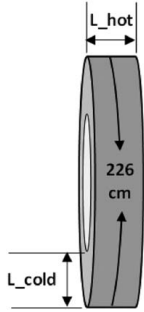
Selective Catalytic Reduction. Thermal NO_x considerations are important at high temperatures in the presence of ambient nitrogen, but when NH₃ is used as a fuel or hydrogen carrier, the fuel-bound nitrogen can lead to fuel NO_x. For this reason, the cracking of NH₃ is ideal to make H₂ available for combustion, while the highly stable N₂ byproduct will inhibit NO_x formation. Interestingly, standard practice for NO_x control in power plants [34] is to use NH₃ for SCR to reform NO_x back to N₂ and O₂ [33], with a dramatic reduction of NO_x to ~3 ppm. Thus, the onboard NH₃ can be used to nearly eliminate the NO_x emissions, which would not be possible with other fuels. As noted in Fig. 7, a separating membrane can be introduced in the future to separate out much of the N₂ formed from catalytic cracking of NH₃ and transfer it harmlessly to the bypass flow. This would reduce the weight penalty of carrying extra NH₃ that is needed for SCR. It should be noted that the NH₃ can be pumped in the liquid phase, and not as a gas, to minimize pumping power requirements and provide the pressure head necessary for all operations.

SCR utilizes the injection of anhydrous NH₃ in the conversion of NO_x into N₂ and H₂O. Assuming 95% of NO_x is NO and 5% NO₂, 1.05 moles of NH₃ to a mol of NO_x is considered stoichiometric for most purposes. However, this generally results in a removal rate of 85%. To achieve higher removal rates, higher than stoichiometric conditions are required. There is a tradeoff in increasing NH₃ input however since this results in more NH₃ slip (i.e., NH₃ emissions). This must then be optimized to limit both NH₃ and NO_x emissions. To complicate things, it is anticipated that as a catalyst ages, it will lose catalytic activity and as such converts less NO_x and allow more NH₃ to slip. To compensate for the loss of NO_x removal, more NH₃ is injected, which in turn increases NH₃ slip. At a certain point, the NO_x and NH₃ emissions will cross the acceptable threshold and the catalyst will need to be replaced or rejuvenated [103].

Along with the NH₃ input parameter, there are plenty of other parameters to be optimized for greater NO_x removal efficiency including the SCR temperature, residence time, mixing strategy, inlet NO_x concentration, and the type of catalyst used, which controls the activity, pressure drop, catalyst pitch, and lifespan. The highest NO_x removal efficiency occurs between 370 °C and 400 °C with higher residence times, better mixing, and more active catalysts also increasing efficiency. For the inlet NO_x concentration, efficiency peaks at 150 ppm and decreases with either an increase or decrease in inlet NO_x concentration. This happens because concentrations < 150 ppm reduce the reaction kinetics, but the increase in kinetics for concentrations > 150 ppm does not warrant the increase in actual NO_x going through [104].

SCR also unfortunately can promote other reactions based upon the catalyst used and other conditions. In general, they promote the formation of N₂O and SO₃, of which SO₃ is not a concern for NH₃/H₂ jet engines. Much research has been primarily done on the reduction of N₂O in SCR based upon the catalyst used and the temperature of the SCR. For example, the use of toluene as a reductant

Table 7 Intercooler design

	Hot	Hot	Cold
	Media	Air	NH ₃
	Length (cm)	13.97	22.86
	Fin type	Offset-strip	Offset-strip
	Fin height (mm)	6.350	3.810
	Fin spacing (mm)	1.4122	1.5875
	Fin thickness (mm)	0.1016	0.1016
	Hyd diameter (mm)	2.1590	2.0828
	Offset length (mm)	1.270	0.635
	Dry weight (kg)		30.9
	Volume (L)		72.2

for the catalyst Pt, along with a high presence of O₂, eliminates N₂O production at all temperatures [102]. This process can be optimized to keep N₂O output low alongside NH₃ and NO_x.

Heat Exchanger and Recuperator. Heat exchangers strongly influence the efficiency, size, and weight of waste heat recovery and fuel processing systems in aircraft propulsion systems. The proposed propulsion architecture uses an intercooler installed in the annular volume downstream of the LPC stage of the engine to acquire heat for evaporating the liquid ammonia fuel. The other heat exchangers in the system diagram shown in Fig. 10, including those contained within the waste heat recovery unit, are described in Ref. [30].

Intercooler inlet conditions were defined using the engine cycle analysis described above, except for the core flowrate. Core flow through the intercooler was varied to achieve a target NH₃ outlet temperature. Limiting the core flow in this manner enables the intercooler to achieve a very low air-side pressure drop ($\Delta P/P < 0.5\%$). A variable flowrate can be achieved in practice using a thermostatically controlled inlet ramp for the core flow entering the intercooler.

An annular plate-fin heat exchanger in a cross-flow arrangement was designed and analyzed using the INSTED program from TTC Technologies² [105] based on the operating conditions given in Table 6. LPC discharge temperatures are less than 450 K, which enables the use of a 6000 series aluminum alloy in the intercooler design. Details of the intercooler design are provided in Table 7, which includes a full definition of the offset-strip fins that were selected to provide heat transfer enhancement for the hot (engine core) and cold (NH₃) flow paths. This design operates in a Reynolds number regime spanning from 1090 to 4150, which is consistent with the dataset Kays and London [106] used to develop the

²<http://www.tctech.com/Insted.aspx>

Table 8 Intercooler performance for ground operations, landing, and cruise

Case	Target NH ₃ temperature (K)	Predicted NH ₃ temperature (K)	ΔP/P air (–)	ΔP/P NH ₃ (–)
A	412.9	414.9	0.43%	1.16%
B	402.9	406.4	0.45%	1.19%
C	381.5	384.6	0.42%	1.24%
D	368.9	374.4	0.43%	0.96%
E	315.7	325.4	0.44%	0.27%
F	303.1	313.1	0.61%	0.26%

governing friction factor and Nusselt number correlations by Manglik and Bergles [107].

Intercooler performance is summarized in Table 8 for ground operations at different ambient temperatures (Cases A, B, C), climb (Cases D, E), and cruise (Case F) conditions. In all cases, the intercooler is able to provide NH₃ fuel at the target temperature while achieving low air-side and NH₃ pressure drops. The intercooler has an estimated dry weight of 31 kg and occupies an annular volume of approximately 72 L. The target NH₃ outlet temperatures require an intercooler design providing effectiveness values ranging from 97.9% to 99.9%. This analysis has shown that these targets can be achieved in a relatively compact (72 L) and lightweight (31 kg) package with a low pressure drop using conventional aviation heat transfer surfaces (i.e., offset fins).

Conclusion

Ammonia appears to be a suitable alternative aircraft fuel to consider with SAF and hydrogen. It is found that ammonia has advantages compared to hydrogen with respect to volumetric energy density, flammability rating, and its availability via existing supply chains. Although it exhibits higher toxicity than hydrogen and SAF, handling experience can be leveraged from the fertilizer and shipping industry. The non-coking properties of ammonia make it a suitable heat sink for compressor intercooling. Instead of burning ammonia directly, this paper proposes to catalytically crack it into hydrogen. Performance data of an existing aircraft engine for a modern narrowbody aircraft were adapted to the novel fuel concept and an intercooler was sized based on expected operating conditions on the ground and during flight.

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Conflict of Interest

There are no conflicts of interest. This article does not include research in which human participants were involved. Informed consent was not applicable. This article does not include any research in which animal participants were involved.

Data Availability Statement

The authors attest that all data for this study are included in the paper.

Nomenclature

C	= compressor
G	= generator
H	= heat source
T	= turbine
T	= temperature, K
APU	= auxiliary power unit
CCA	= cooled cooling air
CH	= cooler
CO _{2eq,100}	= CO ₂ equivalent emissions over 100 years
ETJ	= ethanol-to-jet SAF
FAA	= Federal Aviation Administration
FT-BIO	= Fischer–Tropsch from biomass
FT-DAC	= Fischer–Tropsch direct air capture
GDP	= gross domestic product
gwp100	= global warming potential over 100 years
gCO _{2eq}	= grams of CO ₂ equivalent
HPC	= high-pressure compressor
HPT	= high-pressure turbine
ICAO	= International Civil Aviation Organization
IDLH	= immediately dangerous to life or health
LHV	= lower heating value, MJ/kg
LPC	= low-pressure compressor
LPT	= low-pressure turbine
NFPA	= National Fire Protection Association
NG	= natural gas
ORC	= organic Rankine cycle
PHX	= primary heat exchanger
RH, LHR, HTR	= recuperative heat exchangers
RNG	= renewable natural gas
sCO ₂	= supercritical carbon dioxide
SAF	= sustainable aviation fuel
SCR	= selective catalytic reduction
SFC	= specific fuel consumption
SMR	= steam methane reforming
SNG	= synthetic natural gas
SPK	= synthesized paraffinic kerosene
TCLA	= total leakage and cooling air
TIT	= turbine inlet temperature, K
WCP	= water consumption potential
WHR	= waste heat recovery

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