The Potential Role of Ammonia as a Low Carbon Aviation Fuel

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The Potential Role of Ammonia as a Low Carbon Aviation Fuel

A report for the Aviation Environment Federation
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Executive Summary

The aviation sector faces significant challenges in curtailing its contribution to climate change. Pathways for changes in aviation's greenhouse gas emissions vary, but in all cases new fuels are called for in the coming decades. Without new fuels and/or demand side measures aviation will rely on significant levels of designated carbon dioxide removals (CDR) to keep within global carbon budgets. CDR is currently underdeveloped and in demand across multiple sectors. It is necessary, therefore, to consider more radical options for decarbonising aviation. This report considers the potential for ammonia as an alternative low carbon fuel and as an energy carrier for hydrogen. Based on a detailed literature review of the readiness and prospects for ammonia as an aviation fuel the report finds;

- Ammonia and ammonia/hydrogen blended fuel is at a low technology readiness level. Promising technology pathways exist, but non-technical factors still need to be addressed.

- Ammonia is a widely traded commodity, but this is currently almost entirely for agricultural and plastic products with limited use as a fuel. While hydrogen is being actively pursued as an alternative fuel for aviation, the potential for ammonia fuel is less widely discussed.

- Relatively lower storage and transport infrastructural change is required for ammonia as compared to hydrogen. However, hydrogen's higher gravimetric energy density and its wider fuel cell application is more advantageous in flight.

- Ammonia production is high carbon at present. 'Green' production through renewable energy needs rapid scale-up to replace fossil fuel-based production. Although zero carbon in engine use, more data is needed on the non-CO_2 climate forcing impacts of ammonia as an aviation fuel to fully determine its suitability for tackling climate change.

- The future global green ammonia supply chain is nascent. Renewable electricity and transport costs are key determinants of where, and at what price, green ammonia is produced in the future. Demand for green ammonia from agriculture and plastics will likely also be high. As those sectors pursue decarbonisation, with fewer alternative low carbon feedstock options, increasing competition for limited production capacity is expected.

- Safety certification for handling and storing ammonia at airports needs regulatory consideration given ammonia's reactive properties. Ammonia fuels must also undergo rigorous testing against established aviation industry performance metrics prior to widespread commercial use.

- Commercial barriers stem from reduced payload to accommodate ammonia fuel propulsion, as it requires more volume for on-board storage compared to conventional jet fuel, and the as yet uncertain pricing of green ammonia fuel. Policy to accelerate the uptake of alternative (non-drop-in) fuels such as ammonia and hydrogen to overcome current barriers is lacking. Carbon charges by way of UK ETS and CORSIA are unlikely to drive sufficient investment to bring these fuels to market.

1. Introduction

1.1. Setting the Context – Aviation and Climate Change

The rapid mitigation of greenhouse gas emissions (GHGs), predominantly carbon dioxide (CO_2), is an acknowledged international priority, but one that countries and institutions are as yet failing to deliver on [1]. The window for avoiding the additional climate risks from exceeding an average global temperature increase of 1.5˚C above the pre-industrial average is shrinking rapidly. The remainder of the global carbon budget is 380 $GtCO_2$ (from the beginning of 2023) for a 50% chance to limit warming to 1.5°C [2, 3]. Data based on nationally determined contributions (NDCs) submitted by governments in 2021 illustrate that current mitigation efforts will fall short of limiting emissions to 1.5°C in this century [2].

Aviation presents a particular challenge for meeting global GHG emissions targets. In scenarios that limit warming to 1.5°C with no or limited overshoot, Carbon Dioxide Removal (CDR) technologies need to be deployed for sectors such as aviation, amongst others, given that demand for flying is not assumed to be considerably curbed or cut before 2050 [2]. Between 1960 and 2018, CO_2 emissions from aviation increased by a factor of 6.8 amounting to around 1,034Mt CO_2 in 2018 [4, 5]. Prior to 2020, global aviation emissions had been on an upward trend before an anomalistic drop due to the COVID-19 pandemic (See Fig. 1). However, this impact is expected to be temporary as some projections state that emissions will bounce back by the end of 2023 to early 2024 due to an estimated annual increase in revenue passenger kilometre (RPK) by 3.6% until 2050 [6-9]. In fact, in 2022 the global aviation sector contributed around 2% of global CO_2 emissions [3, 6] rapidly compensating for the dip in emissions– making up about 80% of emissions from pre-pandemic levels (2019) [6]. The overall picture therefore is that trends in the aviation sector continue to run contrary to the needs of international targets to limit climate change risks.

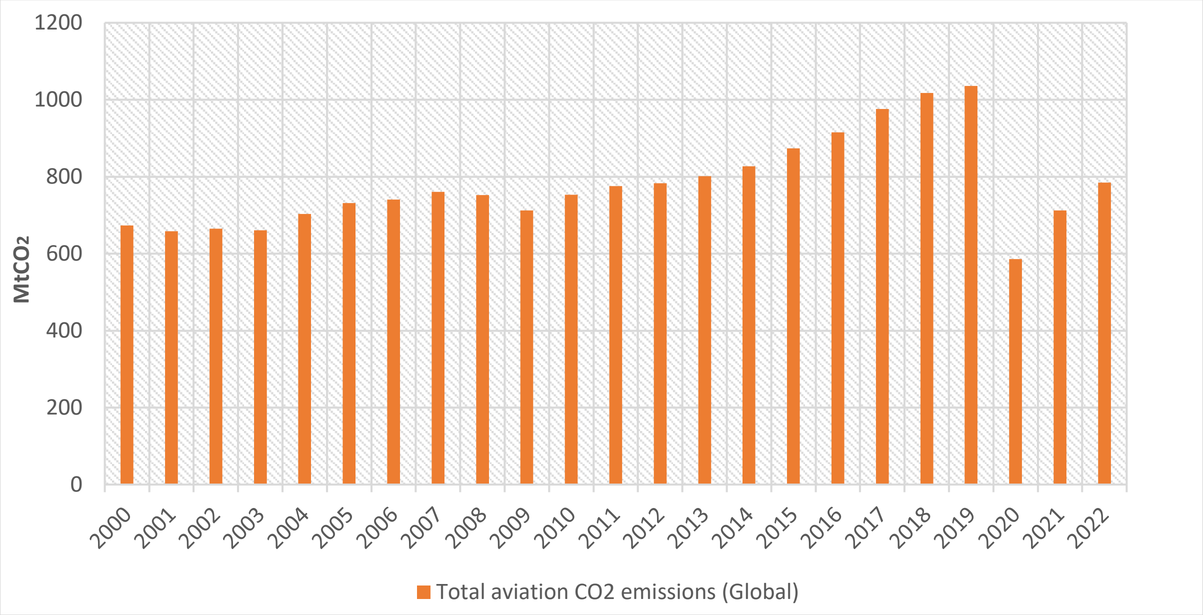

Figure 1 Global total CO_2 emissions from aviation from 2000-2021. Source: [6, 10]

In addition, the inclusion of non-CO_2 emissions emitted at high altitude presents a more accurate picture of the impact of the aviation sector on the climate. Net positive radiative forcing (RF), or warming, from aviation is primarily caused by CO_2, water vapour and nitrogen oxides (NO_X), [5, 11]. Water vapour and soot emissions form contrails, which have a warming affect, as does an increase in cirrus cloud cover from sulphur oxides and sulphuric acid products from high altitude jet fuel combustion. NO_x released at high altitude contribute to both warming – through ozone formation in the upper troposphere – and cooling – through the depletion of methane which is a potent greenhouse gas. Negative RF (cooling) can occur due to sulphate aerosol production. As not all of these emissions are long-lived and well-mixed globally there is some uncertainty as to the precise net global warming impact of non-CO_2 aviation emissions. Studies such as Klöwer, et al. [12] have shown that 4% of total historical anthropogenic warming has been caused by aviation, nearly twice its share of global annual CO_2 emissions. An aviation transition in line with climate goals must consider potential impacts of non-CO_2 emissions even if using sustainable aviation fuels (SAFs) otherwise the sector will continue to contribute to cumulative anthropogenic warming and air pollution.

1.2. UK Aviation Climate Ambition and Future Projections

The role and roll-out of alternative aviation fuels in the UK will almost certainly be determined by target driven policies on emissions. These targets themselves are shaped by particular framings of the UK's contribution to climate change mitigation and how aviation emissions are treated in comparison to those of other sectors. Pathways to meeting these targets also vary in the prominence of alternative aviation fuels to demand change and the offsetting and removal of GHGs, with differing target years and rates of adoption for new fuels implied in each case.

UK aviation emissions, both domestic and international, are effectively included in the country's statutory 'net zero 2050' targets and carbon budget framework. The UK's Climate Change Committee has set a recommended pathway for aviation emissions in its Balanced Pathway scenario for the UK, whereby aviation has a lower burden of decarbonisation compared to other sectors (emissions reduction of ~40% from 2019 to 2050, compared to between 75% to 100% reduction in other sectors) [13] The extent to which UK net zero 2050 policy, and aviation targets therein, is sufficiently ambitious, is contested. Developed countries such as the UK that are responsible for a larger share of historical emissions are called on in the Paris Agreement to take on an equitable share of mitigation and adaptation efforts, i.e. 'Common but Differentiated Responsibilities and respective capabilities' (CBDR-RC) [14, 15].[1] In this respect, the UK's current decarbonisation pathways can be shown to not align with the Paris Agreement's goals, suggesting that the UK needs to double its rate of mitigation to be Paris-compliant [17]. In the case of aviation, the UK has on average accounted for 1.3% of global aviation emissions in the last two decades compared with an estimated 0.89% share of the global population. In recent years there has been a slight decline in UK's share of global aviation emissions, attributed to the rapid increases elsewhere i.e. Asia [9, 18]. However as the sector is working towards a temperature-based target, cumulative emissions are what matter in setting appropriate targets [19]. There is therefore a

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[1] The Paris Agreement reinforces the importance for developed countries to go above and beyond global levels of mitigation in keeping average temperature rise this century well below 2°C, with efforts to limit temperature to 1.5°C. The agreement states: *"…recognizing that sustainable lifestyles and sustainable patterns of consumption and production, with developed country Parties taking the lead, play an important role in addressing climate change…"16. UN, Paris Agreement, U. Nations, Editor. 2015: Paris. p. 27.*

strong case for the UK to take a leadership role in reducing aviation emissions and going beyond current targets.

Within the UK's current 2050 net zero target framework there are also differing pathways for meeting aviation's contribution, with different implications for alternative fuels. The CCC Balanced Pathway for aviation, the UK Government's Jet Zero Strategy and Transport Decarbonisation Plan all vary in the extent to which aviation demand is managed, how quickly alternative fuels are deployed and the role of emission offsetting through offset schemes and carbon dioxide removals (CDR). For example the CCC Balanced Pathway projects UK aviation emissions remaining below their pre-pandemic peak (~40MtCO_2e in 2019) and steadily declining to ~23MtCO_2e/yr by 2050, with demand limited to 25% growth between 2019 and 2050 [20]. The 'Jet Zero Strategy One Year On' proposes greater growth in demand of 52%, revising down passenger growth of +70% in the initial Jet Zero Strategy.[2]

In addition to the overall ambition of emissions targets and the relative contributions of different mitigation options, the capacity and timeliness of CDR may shape the role or fuel switching to reach emissions goals. In the CCC, Jet Zero and Transport Decarbonisation Strategy pathways aviation presents considerable ongoing residual emissions for technological CDR and natural carbon removals to accommodate (19-23 MtCO_2e per year in 2050). The large scale of carbon dioxide removals (CDR) required to meet net zero target is facing cost and capacity uncertainties [21, 22]. Technology based CDR is still an emergent technology that is behind schedule to meet current policy expectations [23]; any further delay in its rollout at scale would mean an even stronger role for demand management or alternative fuels in aviation to meet net zero targets.

1.3. Impetus for Aviation to Transition to Green Ammonia

Due to the infrastructural and technological maturity within the aviation sector, it is particularly difficult to achieve drastic emission reductions from existing fuel platforms if demand for flying remains the same or grows [24, 25]. Fuel efficiency is not on track to compensate for the expected increase in commercial aviation traffic [26, 27]. The majority of the CCC's scenarios presume that the aviation sector will have residual emissions in 2050 meaning that aviation will remain a 'hard-to-abate' sector when it comes to technology solutions, well into the next three decades [28].

Most decarbonisation scenarios for aviation rely on a combination of factors such as the Emissions Trading System (ETS), carbon dioxide removal (CDR), energy efficiency, fuel switching and technological innovation and demand management [6, 9, 25, 29, 30]. The UK's Transport Decarbonisation Plan outlines a combination of technological innovation along with market-based mechanisms and alternative fuels to achieve net zero by 2050. The SAF mandate set to be introduced from 2025 promotes alternative hydrocarbon fuel and infrastructure innovation which is intended to work in conjunction with the UK ETS and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), a global offsetting scheme to address aviation emissions [31].

In efforts to expand fuel and technology options for the aviation sector, the viability of ammonia produced using renewable electricity i.e. green ammonia is being considered by companies such

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[2] Department of Transport, 'Jet Zero Strategy; One Year On', (2023), https://www.gov.uk/government/publications/jet-zero-strategy-one-year-on

as Reaction Engines and Zero Avia for its potential to become part of the fuel mix [32-35]. The ubiquity of ammonia in the agricultural context presents an infrastructural case for producing the fuel at scale - something that other alternative fuels are limited by. However, the current production process of ammonia is both carbon and energy intensive which dissociates ammonia from falling under the sustainable transport fuel category. There are also technical challenges to overcome before ammonia can be demonstrated to be a practical aviation fuel, and beyond this, economic and regulatory questions need to be answered before it could become a mainstream commercial aviation fuel. This report examines the current literature on ammonia as a potential low-carbon aviation fuel and draws conclusions on the role it might have in decarbonising the aviation sector.

2. Viability of Ammonia as an Aviation Fuel

2.1. Operational Factors

At present 230 million tonnes of ammonia are produced annually, making it the second most produced chemical in the world [36], but its current use as a fuel is negligible. Around 80% of ammonia produced is used for fertiliser production which enabled more intensive agriculture in the early 20th century, helping to support population growth [35-37], and it continues to play an important role in supporting the agricultural sector [38]. Other industrial processes such as plastics account for much of the rest of current demand.

For ammonia to be considered a viable zero-carbon option, the production process needs to be overhauled. The current production process is globally recognised as the most efficient production method for large scale production of ammonia [39, 40]. Hydrogen is combined with atmospheric nitrogen with an iron catalyst under a pressure of 150-300 bar at 400°C to 500°C temperature to form ammonia with CO_2 as a by-product [32, 38]. The process is high emitting, contributing up to 1.8% of global CO_2 [36]. This is because 70% of the ammonia produced today uses natural gas as the feedstock for hydrogen via steam methane reformation (SMR); the remainder uses a combination of coal, heavy fuel oil and naphtha [39, 41]. Modern production processes consume 28 GJ/Mt of energy [40] and emit 1.6 tonnes of CO_2 per tonne of ammonia with natural gas as feedstock, while coal, heavy fuel oil and naphtha have CO_2 emissions ranging from 2.5 to 3.8 tonnes of CO_2 per tonne of ammonia [39, 42]. Even with more efficient iterations of Haber-Bosch, the entire production process consumes around 1-2% of global energy [36, 38, 42].

For ammonia to be ‘green’, hydrogen must be generated without unabated fossil fuels such as by electrolysing water and combining it with atmospheric nitrogen via an air separation unit and synthesized using Haber-Bosch, all of which should be powered by renewable energy [32, 35]. Blue ammonia is also a possible transitionary production method as it integrates CCS/CCUS making it low carbon. However, current decarbonisation pathways for aviation have disproportionate reliance on CCUS [43]: there is a need to shift focus away from blue ammonia to green ammonia.

Leapfrogging from grey ammonia (the current method using natural gas) to green ammonia comes with its own challenges. Additional renewable capacity would need to be put in place to make sure green ammonia can be produced at scale. Figure 2 shows IEA estimates of current global electrolyser capacity for green hydrogen (1 GW) by 2030 compared with planned capacity (pipeline of projects) and projected required capacity for their 2050 Net Zero scenario.

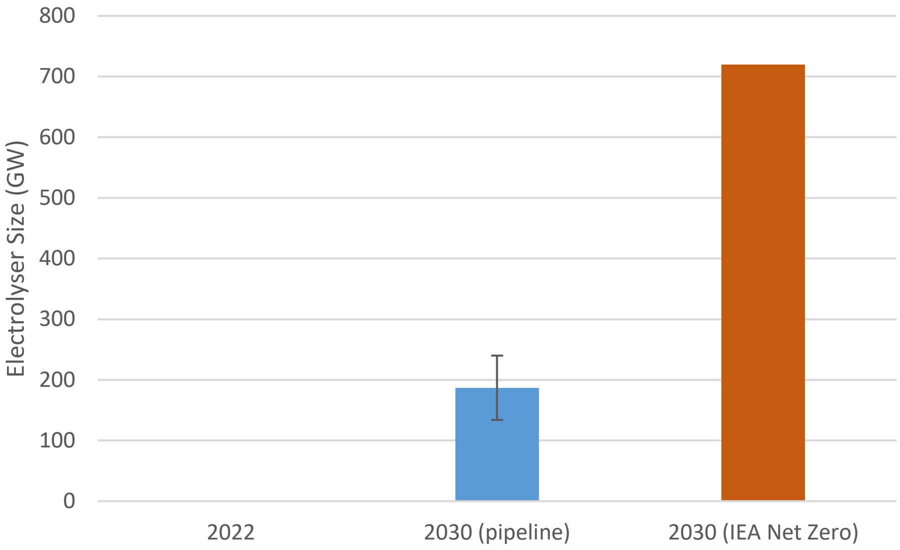

Figure 2: Current and Projected Global Electrolyser Capacity in GW in IEA 2050 Net Zero Scenario[3]

In response to this, newer developments in the field of ammonia production are bypassing the Haber-Bosch process altogether to avoid continued use of this energy and capital-intensive method and look to more efficient ways of producing green ammonia. Cleaner and more energy efficient methods of synthesising ammonia such as artificial photosynthetic nitrogen reduction which mimics biological nitrogen fixation using solar energy (photochemical production) and electricity (electrochemical production) are being explored [44-46]. Other production routes such as plasma-enabled synthesis (i.e. using plasma to create a highly reactive environment for chemical reactions at relatively lower temperatures reducing the overall energy requirement) are still under development. So far this approach has only proven to be able to cater to small scale needs via localised production of green ammonia [47, 48] though these novel techniques are at the early stages of development. Research on scalability is now needed to enable understanding about whether these production methods can meet both existing demand from the agricultural and refrigerant sectors and additional demand from the transport sector.

When examining the viability of green ammonia as an aviation fuel, it is vital to consider its feasibility in the mid-stream supply chain. This section assesses factors such as on-site storage, transport, bunkering, safety, and certification needed to use any alternative fuel at scale. A study last year by Otto et. al [27] examined ammonia as an aviation fuel and included a comparison of the operational factors for the different alternative energy options for aviation presented in Table 1. It is evident that at this stage SAF has advantages over the alternatives as a short-term to mid-term option because of minimal infrastructure changes.

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[3] See IEA https://www.iea.org/reports/electrolysers

Table 1 Shows a comparison of the feasibility of alternative aviation fuels adopted from Otto, Vesely [27]

Kerosene Baseline	Battery-electric	H_2 fuel cell	H_2 turbine	SAF	NH_3
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 > 8047 km
Aircraft Operations	Same or shorter turnaround time; weight remains constant throughout a flight negatively impacting range	1-2x longer refueling times for up to short range; special safety standard	2-3x 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 (liquid hydrogen) 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	Minimal – existing infrastructure (e.g. fertilizer)

Despite the existing know-how on how to transport and store ammonia in the fertiliser industry, safety regulations will have to be created that fully consider ammonia's high toxicity and corrosiveness in different inland applications [49]. Containment zones around airports will be much greater compared to conventional aviation fuel in case of potential leakage and accidents [50]. As pressure is high for the aviation sector to maintain its safety standards on land and in the air, the lack of existing safety regulations around ammonia handling in airports and airplanes is a hurdle in adopting this fuel.

If the UK were to continue to import the majority of its ammonia for consumption, rather than manufacture it within the UK, then standards for mass transportation of ammonia to various sites from producer countries to the UK will also need to be put in place. Green ammonia is most likely to be produced in countries with large renewable energy capacity. Countries such as Australia, Brazil, Chile, Morocco, and Argentina are set to be the first movers [51]. There are up to 17GW of planned renewable energy projects for electrolysis solely to produce green hydrogen globally [52]. Europe has the largest planned increase in renewable energy (RE) capacity at 108.9 GW for the production of green hydrogen largely driven by the EU's net zero 2050 targets [52]. If the EU delivers on these plans, the UK could potentially have a supply of green ammonia from the EU, however there are uncertainties surrounding how many of these planned projects will materialize.

Globally, since 2018 around 15 Mt (annual capacity) worth of additional green ammonia plants are planned to be set up by 2030 [53]. A study by Wang et. al. [54] examined ammonia-based green corridors and concluded that since ammonia transportation is much cheaper than its production costs, it is more economical to produce it in a “low-cost location” and transport it, often by ship, to demand centres. It is likely that the aviation sector (and other sectors where ammonia will play a role) would use existing inter-regional and intra-regional distribution networks in place via pipelines, rail, road and ships for transporting ammonia [55] enabling an easier transition.

The adoption of any alternative fuels (especially non-hydrocarbon-based fuels) requires rigorous testing and certification to ensure they meet safety and operational metrics. Within the aviation sector, fuel certification and approval processes are time-consuming and expensive [56, 57]. The British Standards Institution (BSI) applies the American Society for Testing and Materials (ASTM) standard for aviation fuels used by UK airline operators. Jet A-1 aviation fuel, which is widely used within the UK, must meet several standards such as ASTM D1655-21c and DEF STAN 91-091 (Defence Standard), IATA Guidance Material, and NATO code F-35 specifications [58, 59]. The ASTM International has various pathways through which both conventional and novel sustainable fuels get certified and approved, which is widely used to standardize fuels. ASTM D4054-21a is the certification criterion for novel fuels and is used to evaluate new aviation turbine fuels and fuel additives including drop-in fuels [60]. Newer fuels not only have to perform to conventional fuel standards and provide sufficient propulsion but also adhere to technical metrics, crucially, their ability to reignite during cruise. Jet A1 properties are well suited for on-board infrastructure (discussed further below) as performance-based metrics suggest that companies have to sacrifice payload and range with non-hydrocarbon based fuels [61, 62]. Properties of Jet A1 such as high energy density, viscosity, aromatic content and its ability to be safety stored in flight under extreme conditions make it challenging for alternative fuels to compete with conventional or other drop-in fuels in relation to operational factors. [63, 64].

2.2. Technical Factors

The section aims to understand the technical aspects and applications of green ammonia as a fuel and its potential as a hydrogen carrier. Since technological step change is hard within the aviation sector compared to most others [24], it is valuable to examine the current technical landscape to further understand the pace of transition. Studies that have explored a transition to green ammonia as a transport fuel have examined key physical properties that make it technically advantageous in some ways and disadvantageous in others [42, 65-69]. Ammonia is often compared with hydrogen as it can also be a hydrogen carrier. This is largely due to the fact that ammonia has a higher hydrogen content by volume than hydrogen itself [27]. Liquid ammonia can be stored at room temperature (25°C) at 0.99 MPa or in -33°C in atmospheric pressure in insulated tanks [69, 70].

Table 2 Comparison of physical properties of ammonia and hydrogen with Jet A-1 adopted from Aziz et al [69] and Goldmann et al [71]

Properties	Unit	Compressed Hydrogen	Liquid Hydrogen	Liquid Ammonia	Jet A-1
Storage method	-	Compression	Liquefaction	Liquefaction	Liquefaction
Temperature	°C	25 (room)	−252.9	-33	176
Storage pressure	MPa	69	0.1	0.99	-
Gravimetric energy density (LHV)	MJ/kg	120	120	18.6	43.2
Volumetric energy density (LHV)	MJ/L	4.5	8.49	12.7	34.9
Gravimetric hydrogen content	wt%	100	100	17.8	-
Volumetric hydrogen content	kg-H_2/m^3	42.2	70.8	121	-

There are various methods via which ammonia can be used as a fuel, namely direct ammonia combustion, ammonia and hydrogen blend, ammonia conversion to hydrogen using the latter as the fuel, and ammonia in fuel cells. While ammonia's strengths have been proven as an energy carrier, there is an increasing interest in ammonia as a fuel itself. However, there is limited real-world testing at this stage of fuel development.

Life cycle assessments (LCA) in the shipping sector, where ammonia fuel use is more advanced, indicates that on a full life cycle 'well to wake' basis ammonia fuel combustion may have a much lower global warming potential (GWP) than marine fuel oils, where renewables are used to produce ammonia [72, 73]. However, the production of nitrous oxide (N_2O) is noted as an important uncertainty which the overall GWP of ammonia fuels is sensitive to. N_2O is a long lived and powerful greenhouse gas with a 100 year GWP that is 298 times that of CO_2 [74]. A proportion of nitrogen slippage through the supply chain, and more acutely in combustion, can lead to N_2O formation, though exactly how much N_2O is produced is unknown [75]. The lack of real world data on ammonia combustion in applications such as shipping and aviation means broad assumptions have to be used in LCAs [73]. Based on their range for N_2O kg/kWh Kanchiralla et al. [73] in their LCA of ammonia fuel appear to assume between 0.005% and 0.05% nitrogen in ammonia becomes N_2O in combustion – with ammonia fuel GWP increasing +25% across this range – but a high level of uncertainty is noted in the study. The issue is important as Wolfram et al. [75] find that the climate change mitigation benefits of ammonia fuels would be completely offset if 0.4% of nitrogen in ammonia fuel became N_2O. A clearer understanding of N_2O formation from ammonia in aviation is therefore essential to fully understand its climate impact.

LCA (well-to-wake) comparison of Jet A-1 with green ammonia and green hydrogen suggests an 80% reduction in gCO_2eq [27]. One of the challenges with ammonia as a direct fuel is its low combustion rate, meaning that it requires a combustion promoter (which can be fuels like diesel or hydrogen) for a sustained ignition [76]. A study by Kobayashi et. al. [32] finds that blending hydrogen with ammonia leads to enhanced flammability without needing to store hydrogen separately. This blend can be stably combusted in gas turbines and reduce NO_x emissions compared to combusting pure ammonia [77]. Additionally, hydrogen's high gravimetric density and combustion rate coupled with the convenience of storing and transporting ammonia is perhaps a selling point for an ammonia and hydrogen blend [69, 78]. In their assessment of sustainable aviation fuel alternatives, the Aerospace Technology Institute (ATI) findings suggest that while cracking ammonia (breaking it down to generate nitrogen and hydrogen) increases its efficacy in a gas turbine it does not alleviate the issue of NO_x production [78].

The cracking process has piqued the interest of academics as well as companies testing ammonia as a jet fuel [71], the idea being that cracking the right amount of ammonia into a blend of ammonia, nitrogen and hydrogen results in an on-board fuel that behaves much like Jet A-1 [79]. This is being tested at Reaction Engines who, in collaboration with the Science and Technology Facilities Council (STFC) are configuring aircraft engines to enable retrofitting technology to cater to the short-haul market [80]. More recently, Aviation H_2, have selected the cracking method largely due to the high hydrogen content in ammonia as well as easy storage and transport, although this test has only been conducted on a charter flight [81].

Despite higher efficacy of ammonia fuel blends, the ATI cites NO_x and water vapour as reasons for ruling out ammonia, as NO_x contributes to local air pollution and water vapour contributes to global warming when released at altitude. However, residual NO_x emissions which are typically addressed using an after-treatment process called selective catalytic reaction (SCR) which converts NO_x into nitrogen and water have not been tested in jet engines yet [79]. Similarly the potential for N_2O production from nitrogen slippage from ammonia through the supply chain and its impact on GWP needs to be better understood before a more accurate LCA value for ammonia-based combustion can be defined [75]. Ammonia combustion is therefore unlikely to eliminate the non-CO_2 impacts of flying even if it generates no CO_2, and more data is needed from use-phase examples.

The application of ammonia in a fuel cell is both carbon and NO_x free, while potentially reducing N_2O emissions resulting from in the use-phase relative to combustion [75]. A fuel cell (FC) is an electrochemical medium that converts hydrogen and oxygen reaction into electricity [82]. Its compatibility with ammonia varies based on the type of fuel cell. Use of ammonia in a Solid Oxide Fuel Cell (SOFC) in high temperatures yields strong results, with similar technical performance to that of a hydrogen fuel cell [79]. Direct use of ammonia in a SOFC means that it can provide high efficiency and power needed for aircraft [70]. In a more recent study by Baroutaji et. al. [83], there is detailed assessment stating that hydrogen SOFCs can replace the aircraft's auxiliary power unit (APU) that is conventionally powered by a gas turbine or work with the existing system (in a hybrid mechanism). The APU plays a crucial role within an aircraft providing back-up power during cruising and main power when stationary. Using hydrogen fuel cells in this application could potentially reduce fuel consumption by 40% during cruise and 75% when stationary [83, 84]. The Proton Exchange Membrane fuel cell (PEMFC) is another option however ammonia would need to be decomposed back into hydrogen as ammonia's toxicity can poison the proton exchange membrane. Moreover, PEMFC's commercial use and higher technological readiness compared to SOFCs makes it harder for ammonia to be considered as a direct fuel via FC application [85]. Generally, more research has been undertaken into the efficient use of hydrogen fuel cells in aviation than in fuel cells for ammonia, mainly because hydrogen can be used as the primary fuel in both types of fuel cell suited for aviation applications [83, 86, 87]. It is important to note that implementing a fuel cell system on board means reconfiguring it to ensure that the materials and components meet weight requirements [88].

2.3. Economic Factors

As a product, green ammonia is still at a nascent stage of development, making its conventional counterpart a more attractive option for now. However, its prominent role in the UK's transition into a hydrogen economy could have positive impacts on the CAPEX and OPEX of green ammonia over time. This is bound to be a factor in the likelihood of its uptake within the aviation sector as fuel can account for up to 70% of direct operating costs for a wide-body aircraft > 300 seats and up to 35% for a turboprop plane with 20-60 seats [89]. The cost of renewable energy is an important variable in determining the cost of green ammonia production; it is cheapest to produce green ammonia where renewable energy prices are cost competitive with SMR + CCS (i.e., blue ammonia). Under optimal conditions, solar powered regions such as Chile and Morocco are ideally placed for this [42]. The wide-ranging costs of solar in different geographic regions makes it difficult to determine an average CAPEX. Localised assessments such as the one in Guerra et al. [90] presents the results of a techno-economic assessment of operating a green ammonia production plant in Chile and transporting the ammonia to Japan. The paper concludes that the cost of green ammonia in Japan needs to be €400/ton (approx. £344) to ensure that the payback period is under 10 years and therefore represents an attractive investment option [90]. In their study Cheliotis et al. [91] makes a comparison between the CAPEX and OPEX of ammonia and hydrogen until 2030 and suggests that even though initial capital costs will be higher for green ammonia, this will decrease over time due to technology maturity. Subsequently the cost of ammonia fuel will decrease as infrastructure to transport, store and handle it in large quantities is already in place, unlike for hydrogen [91].

There are external factors such as carbon pricing that could impact the economics of green ammonia. In their study, Chehade and Dincer [37] found that the OPEX of small-scale green ammonia plants and large-scale conventional ammonia plants are determined by feedstock availability, transport, CO_2 emissions limits and carbon price. All else being equal, imposing carbon pricing on conventional ammonia production can improve OPEX of green ammonia over time [37]. Several techno-economic assessments of ammonia have been conducted largely driven by its potential role in the shipping sector with very few including the aviation fuel supply chain into the mix [42, 91-95].

2.4. Policy Factors

Policy must consider radical technology shifts for aviation decarbonisation, specifically long-haul segments, as the UK faces pressure to meet its net zero targets with each successive year. Factors such as lock-in infrastructure, strict safety and weight regulations, and complex fuel certification issues can all delay ambitious policy being implemented [96]. In the interim, carbon pricing is sought after by manufacturers of novel propulsion technologies as well as some national governments as market-based measures like ETS and CORSIA should in theory inject some investment into the development of new technologies to encourage expansion of the infrastructure required for alternative energy production [97]. However, those policies have been critiqued in literature [98-101] and CORSIA is the only global policy instrument in place for international aviation. Currently, ICAO policies are narrowly focused, with an overarching focus on long-term goals, evidenced by the fact that infrastructure expansion has only recently been a part of the discussion. Within the UK, in 2020, the Government – in partnership with Ecuity, STFC, Engie and Siemens – conducted a feasibility study on large-scale ammonia cracking to hydrogen utilisation, with all segments of transport (including aviation) projected to be likely end-users [102]. These much-needed changes come at an arguably tricky period as the aviation sector is making efforts to recover their financial losses during the COVID-19 pandemic. The adoption of any meaningful ambition to drive a low-carbon fuel transition within the aviation sector is a recent development. As a result, the current policies do not encompass green ammonia in the context of aviation or the necessary efforts for broader infrastructural changes. This is a significant reason why drop-in fuels are being advocated as a transitional solution, considering the gradual pace of technological advancements [103].

3. Discussion

Top-line analysis of the academic and grey literature suggests that green ammonia's readiness level in the context of aviation is relatively low, with several upstream issues yet to be solved. Its long-term technical viability is not yet proven for any sector, let alone aviation, so wider supply chain network issues cannot be addressed. As a result, the further downstream the fuel supply chain examined in this study, the larger the barriers, as ammonia's use-case in aviation is still in its very early stages. More consideration of non-CO_2 gases, notably N_2O, is needed so that the overall impact of the fuel – particularly in combustion processes – on the climate is understood and mitigation measures are applied. Additionally, there is no global large-scale production of ammonia from renewable sources as of yet [104]. While there are plans for electrolyser projects globally, it is still to be determined how much of that will be directed towards transport fuel use as there will be competing demands from sectors with fewer low-carbon alternatives, such as fertiliser production – which already have infrastructure and procurement for ammonia in place (see Figure 2).

Currently, the aviation sector is going through a period where it is largely focused on financial recovery post COVID-19 [105, 106]. While policy instruments such as carbon taxes and regional ETS mandates are important, if they are not structured to sufficiently incentivise and support new technology adoption, they could stall a sectoral transition as large swathes of investments are required to develop and scale up new technology. The sector is arguing for revenue raised from carbon markets to be redirected into supporting new technology uptake instead of going to HM Treasury, however, within the UK there is no ring-fencing of funds from the UK ETS [107]. Carbon pricing alone may not deliver new technology adoption fast enough without more targeted policies in addition.

Additionally, policies around novel and uncertified aviation fuels are likely to be influenced by public perception, especially in relation to green ammonia [55]. Compared with shipping, this will carry more weight within the aviation sector as it is more consumer facing, and there are likely to be safety concerns surrounding human exposure to potential accidents and leakages. Work undertaken by companies like Reaction Engines and Aviation H_2 are aiding the technical viability of ammonia on board. However, in the absence of fuel cells NO_x emissions will remain a concern.

4. Conclusion

Aviation faces significant challenges in contributing to economy-wide efforts to meet climate change goals. The rate and type of change required by the sector varies depending on how decarbonisation is translated into national and sectoral targets, the relative roles of demand management and technology change to meet those targets, and the extent to which CDR can balance residual emissions. Considering the cumulative and future emissions of the aviation sector, in all of these permutations the timely rollout of technological solutions has a significant role in facilitating a sector-wide transition.

This report focuses on green ammonia's potential viability as an aviation fuel. It is important to address the technical barriers associated with direct ammonia use, as meeting fuel performance criteria based on the properties of Jet A1 fuel is challenging. Presently, the industry primarily focuses on conventional fuel supply and usage, favouring drop-in solutions like SAF, rather than embracing new fuels like ammonia that necessitate changes in airport infrastructure and aircraft design. Although blends of hydrogen and ammonia show promise, scaling up on-board cracking for larger aircraft segments remains a hurdle.

Ammonia's potential role in aviation extends beyond its use as a fuel itself as it can be used as a medium to transport and store hydrogen for use in aircraft. While it can be advantageous to convert hydrogen to and from ammonia for transport, there are energy penalties in conversion and environmental risks from handling ammonia in this way that are still to be addressed [108]. A range of scenarios for development of green hydrogen production infrastructure, where this is localised and how it is best transported, exist and it is too early to definitively say what role ammonia will have in a future hydrogen economy. This does also mean that the UK, which has negligible ammonia production domestically, could realise opportunities in green ammonia through green hydrogen capacity building. In any scenario aviation will face competition from other sectors to secure nascent green hydrogen and ammonia production.

Mid-stream challenges for ammonia encompass modifying airport and on-board infrastructure to store and utilize ammonia. This report emphasizes the importance of considering the long-term implications of the aviation industry's transition to green ammonia. While conventional fuel supply and use are currently the industry's primary focus, it is crucial to recognize the potential of new fuels like ammonia and the necessary changes in infrastructure and aircraft design that come with them. This infrastructure lock-in to Jet A1 fuel poses challenges for any transition, as the consequences of such changes are likely to have long-term effects. Hence, the longevity and effectiveness of ammonia and its fuel supply chain are crucial. By investing in necessary modifications, the industry can pave the way for a more sustainable future.

Non-CO_2 emissions mean aviation's total contribution to human induced global warming is estimated to be around double that of its CO_2 emissions alone [12]. It is essential therefore to acknowledge the complexity of non-CO_2 emissions in aviation. The lack of data around nitrogen slippage N_2O arising from ammonia fuels is a key uncertainty in establishing the suitability of ammonia-based fuels for climate change mitigation. It is therefore important that emerging ammonia engine technologies monitor and minimise N_2O emissions to ensure reduced global warming impacts before the technology is widely adopted. Consideration must be given to how alternatives like ammonia, and particularly ammonia/hydrogen blends, contribute to non-CO_2 emissions if and when they are deployed.

Ultimately technological solutions alone will not be sufficient to achieve the deep decarbonisation needed within the required timeframe while accommodating the planned growth in demand [109]. Given the scale of decarbonisation required by the Paris Agreement, it is crucial to incorporate demand management strategies to achieve meaningful reductions in emissions, particularly in the aviation sector [22]. Demand management strategies can take various forms, such as promoting alternative modes of transportation, which can be applied in addition to policies encouraging more efficient aircraft designs, and implementing policies that incentivize the use of low-carbon fuels. These measures can help alleviate the pressure on the industry to solely rely on technological advancements for emissions reductions. Furthermore, by reducing the overall demand for aviation fuel, resources can be redirected towards the development and production of alternative fuels, including green ammonia. This would not only contribute to the decarbonisation efforts in aviation but also create new economic opportunities and promote domestic production capabilities.

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