Transitioning to low emissions domestic aviation in New Zealand

A detailed technical options analysis

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Ara Ake
Future
Energy
Development

Contents

Preface

Ara Ake, New Zealand's Future Energy Centre, has conducted an independent, order of magnitude analysis on the technical options to reduce the emissions of domestic aviation in New Zealand. The options considered are green hydrogen, sustainable aviation fuel (including eSAF) and electrochemical batteries. These are all compared to the incumbent, Jet A fuel, which has been used as a baseline.

This document aims to contribute to the development of greater innovation and collaboration opportunities in the energy and aviation sectors in New Zealand.

This report was primarily authored by Dr Jono Barnard, Research and Insights Manager at Ara Ake, and has been reviewed externally by:

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- Distinguished Prof. Robert McLachlan in Applied Mathematics at Massey University, Palmerston North and expert in New Zealand's domestic aviation sector; and
- Dr. Jayant Mukhopadhaya, Senior Aviation Researcher focused on the feasibility of zero emissions aircraft at the International Council on Clean Transportation in Berlin, Germany.

Summary

Domestic aviation in New Zealand contributes close to 3% of energy sector emissions and over 1% of national gross emissions. The aviation sector has committed to the International Air Transport Association (IATA) target of net zero by 2050 and when examining the potential technology improvements (under the *avoid-shift-improve* framework), typically three technical options are considered to replace jet fuel: green hydrogen, sustainable aviation fuel (SAF) and electrochemical batteries. This report provides a detailed analysis of the various technical options to abate emissions in New Zealand's domestic aviation sector.

Potential decarbonisation options

Green hydrogen

Assuming aircraft design and airport infrastructure challenges can be overcome, green hydrogen is a realistic emissions reduction pathway for domestic aviation in New Zealand. Modelling has shown an expected average reduction in emissions of 94% when compared to Jet A fuel, whilst also achieving similar take-off and landing weights despite cryogenic requirements.

When considering reasonable improvements to technology efficiency alongside expected aircraft changes in the future domestic fleet, suitable energy carrier volumes can also be achieved (keeping in mind that if hydrogen was prioritised for domestic aviation, new purpose-built aircraft will likely replace incumbents rather than relying on retrofits and efficiency improvements).

Water consumption to produce the required amount of hydrogen through electrolysis is reasonably low, however electricity requirements will likely exceed 15% of national projected demand.

Sustainable aviation fuel (SAF)

SAF has significant advantages to the other low emissions alternatives due to being a drop-in fuel with minimal infrastructure or airplane technology changes and this work has shown it could be used as an alternative to hydrogen to decarbonise domestic aviation. Saying that, SAF can only achieve similar levels of decarbonisation to hydrogen if using specific feedstocks such as used cooking oil, waste biomass, or through the combination of hydrogen and direct air-captured carbon to produce e-kerosene (or eSAF).

When considering supply and demand, used cooking oil isn't really a suitable SAF feedstock for New Zealand as over 2% of global supply would be needed to abate the emissions from the domestic fleet (which makes up less than 0.1% of global demand). However, approximately three quarters of the locally sourced supply of waste woody biomass could decarbonise the sector.

Importantly however, domestic aviation is expected to make up only 10% of liquid fuel demand as we approach 2050 and the use of available waste biomass supplies needs to be carefully considered alongside the emissions reduction pathways of other sectors, especially those which are hard-to-abate with no other realistic *improve* options (such as international aviation and shipping).

With eSAF, in theory there are few constraints on the supply side to produce the required hydrogen and carbon, alongside the benefit of not needing new aircraft. However, the production process is expensive and highly energy intensive, requiring more than twice the electricity than if domestic aviation was decarbonised with liquid hydrogen and approximately ten times more than SAF produced using waste biomass.

Electrochemical batteries

Current battery technology has significant limitations which prevent it from being a viable option without completely overhauling the domestic network. Due to their low specific energy (MJ/kg), batteries are far too heavy to meet New Zealand's domestic travel needs whilst also maintaining a comparable passenger capacity.

A sixteen times increase in specific energy to the maximum theoretical value associated with an electrochemical battery (4,000 Wh/kg) would enable the majority of domestic flights to use battery-electric technology whilst also meeting aircraft take-off and landing design requirements. Unfortunately, achieving such large energy densities is unrealistic and significant changes to route length – or aircraft size – would be required for domestic aviation to be fully electrified.

Looking forward

Through a fundamental physics approach, this report has identified potential technical options to replace jet fuel in New Zealand's domestic aviation sector. However, there are still critical barriers to overcome as these options are pre-commercial on the technology readiness level (TRL) scale.

If a decision is made to reduce domestic aviation emissions through the *improve* approach using green hydrogen, SAF, or a combination of the two, entirely new industries, infrastructure, supply chains and regulatory frameworks would need to be developed.

Definitions

Energy carrier

A substance (fuel) or phenomenon (energy system) that contains energy that can be later converted to mechanical work or heat or to operate chemical or physical processes.

Jet A

A liquid fuel, produced through the refinement of fossil hydrocarbons, designed for use in aircraft powered by gas-turbine engines.

Sustainable aviation fuel (SAF)

A liquid fuel, almost chemically and physically identical to Jet A, produced through the refinement of non-fossil fuel-based feedstocks.

eSAF

A type of sustainable aviation fuel produced through combining green hydrogen with direct air-captured carbon dioxide.

Electrochemical batteries

A device containing an electrochemical cell or a series of electrochemical cells which can store or generate electrical energy via reversible chemical reactions.

Hydrogen

Hydrogen is the lightest, most abundant chemical element in the universe and is an energy carrier which can either be burnt to produce heat or used in a fuel cell to produce electricity. Low emissions “green” hydrogen is produced through electrolysis using water and renewable electricity.

Electrolysis

A manufacturing process which uses direct electric current to drive an otherwise non-spontaneous chemical reaction.

Fuel cell

An electrochemical cell that converts the chemical energy of an energy carrier and an oxidizing agent into electricity via chemical reactions.

Cryogenics

The science that addresses the production and effects of very low temperatures e.g. the liquification of hydrogen gas.

Specific energy (MJ/kg or Wh/kg)

The total energy stored in one kilogram of an energy carrier. Specific energy can be represented by megajoules per kilogram or watt-hours per kilogram, where 1 MJ/kg = 277.78 Wh/kg.

Turboprop

A variant of a jet engine that has been optimised to drive a propeller to generate propulsion.

Turbofan

A variant of a jet engine that that uses a combination of combustion and a fan to generate propulsion.

Fuselage

The central body portion of an aircraft designed to accommodate the crew, the passengers and/or cargo.

Introduction

Domestic aviation in New Zealand contributed 824.6 kilotonnes (kt) of CO_2e in 2021.[1] This is equivalent to approximately 5.9% of transport emissions, 2.6% of energy sector emissions and 1.1% of national gross emissions. Pre-COVID, these latter values were 3.3% and 1.4% respectively and, considering recent upwards trends, there is an expectation that these emissions will be returning to similar levels due to an industry bounce back. Domestic aviation emissions are the result of close to 200,000 domestic flights per year (≈22 per hour). Approximately 16 million passengers board these flights to travel a total distance over 80 million kilometres and flight remains to be among the only options to quickly travel in New Zealand (both intra- and inter-island) due to limited rail or other efficient, long distance transport alternatives.[2] As a result, New Zealand has among the largest per capita domestic aviation emissions in the world and, as easier-to-abate sectors of the economy are decarbonised, domestic aviation's relative portion of national gross emissions will likely increase.[3]

Jet A fuel combustion is the primary method to provide the domestic (and international) aviation fleet propulsion to get from A to B, however as we transition to a low carbon economy, we will need to consider the various options to reduce aviation emissions. This is typically viewed through the *avoid-shift-improve* (ASI) framework, which reflects the decarbonisation opportunities for socio-cultural, infrastructural, and technological change.[4] Under this framework, emissions reduction opportunities exist in the form of *avoiding* business or personal travel, *shifting* to low emissions long-distance transport such as rail or through *improving* plane technology through the use of different, low carbon sources of energy.

This report focuses on the three technical options being typically considered to *improve* aviation emissions: green hydrogen, which can be created via electrolysis of water using renewable electricity; sustainable aviation fuel (SAF), a drop-in fuel which can be produced from a range of feedstocks; and electrochemical batteries, similar to those found in electric vehicles.

Given the recent publications by Air New Zealand,[5] the New Zealand Hydrogen Aviation Consortium,[6] and New Zealand-based academics,[7,8] Ara Ake has conducted a detailed analysis on the various options to abate emissions in New Zealand's domestic aviation sector. The purpose of this report is to present the findings of this analysis and to independently consider the technical viability of each *improve* option.

Modelling approach

In late 2017, the Ministry of Transport conducted a market analysis of domestic aviation and made projections out to 2043. These projections included aircraft fleet, number of flights and passengers, average flight distance and total jet fuel consumption. The database used to support the modelling was developed by Sabre AirVision Market Intelligence and since then, no similar open-source data has been made available.

In the context of this modelling, the actual projected values are not specifically of interest, but do provide a suitable baseline over a set period of time to enable a comparison with the low carbon propulsion alternatives. The base modelling outputs are provided in Appendix A.

Figure 1 details the flight distribution and the associated jet fuel usage distribution with respect to the change in domestic fleet aircraft over the modelling time period (2016-2043). The 4 aircraft categories include Airbus A320,[i] ATR 72, Bombardier Dash 8 Q300 and small planes (such as Beech 1900D or miscellaneous Cessna models). The various specifications for each are included in Appendix B.

The jet fuel usage distribution, or emissions distribution (as emissions and fuel usage are directly proportional), shows an expectation that over 85% of domestic aviation emissions will be associated with A320 flights in 2043, despite these aircraft only expecting to be associated with effectively one in two flights in the same year (55% flight share). This is an increase from 60% of emissions and one in four flights in 2016. The remainder of 2043 domestic aviation emissions are expected to be mostly contributed by ATR 72 aircraft (14%) which will make up 40% of flights.

Figure 2 displays the average distance each aircraft category typically travelled in 2016. It is worth noting that these averages are approximately 5-10% greater than the 2043 projections (mostly due to larger planes travelling shorter distances), however this buffer will provide a more conservative modelling output in terms of emissions and other technicalities such as take-off and landing weights.

As one would expect, the largest aircraft (A320) travels the largest distance per flight on average (666.2 km) with routes such as Auckland or Wellington to Christchurch (758 km and 302 km), Auckland or Wellington to Queenstown (1,037 km and 645 km) and Auckland to Wellington (490 km). ATR 72 and Dash Q300 cater to the regions (Wellington to New Plymouth, 261 km; Dunedin to Christchurch, 309 km) and, in today's market, are almost used interchangeably. Small aircraft typically only fly shorter routes (such as Blenheim to Wellington, 74 km; or Auckland to Whangarei, 139 km).

Considering fuel usage, the total energy used per flight can be determined using the specific energy of jet fuel (≈43.5 MJ/kg=12.1 kWh/kg). The theoretical energy requirement for the average flight in a given aircraft can be determined by the efficiency of converting the energy in jet fuel to propulsion. These overall efficiencies range from 20% for turboprops (ATR 72/Dash Q300) to 35% for turbofans (A320) (see Appendix B).[9] The actual and theoretical energy requirements for the average flight taken by each aircraft are presented in Figure 3.

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[i] It is important to note that A320(ceo) aircraft are beginning to be phased out by A320neo aircraft in New Zealand, which Airbus quotes 'delivers 20% fuel savings and CO_2 reduction compared to the previous-generation'. At present, 53% of the A320s in Air New Zealand's fleet are associated with the model in the future projections.

Figure 1: Domestic aviation flight distribution by aircraft over time (left); Domestic aviation emissions (jet fuel usage) distribution by aircraft over time (right). The current Air New Zealand fleet distribution is shown with the coloured dots on the left plot.

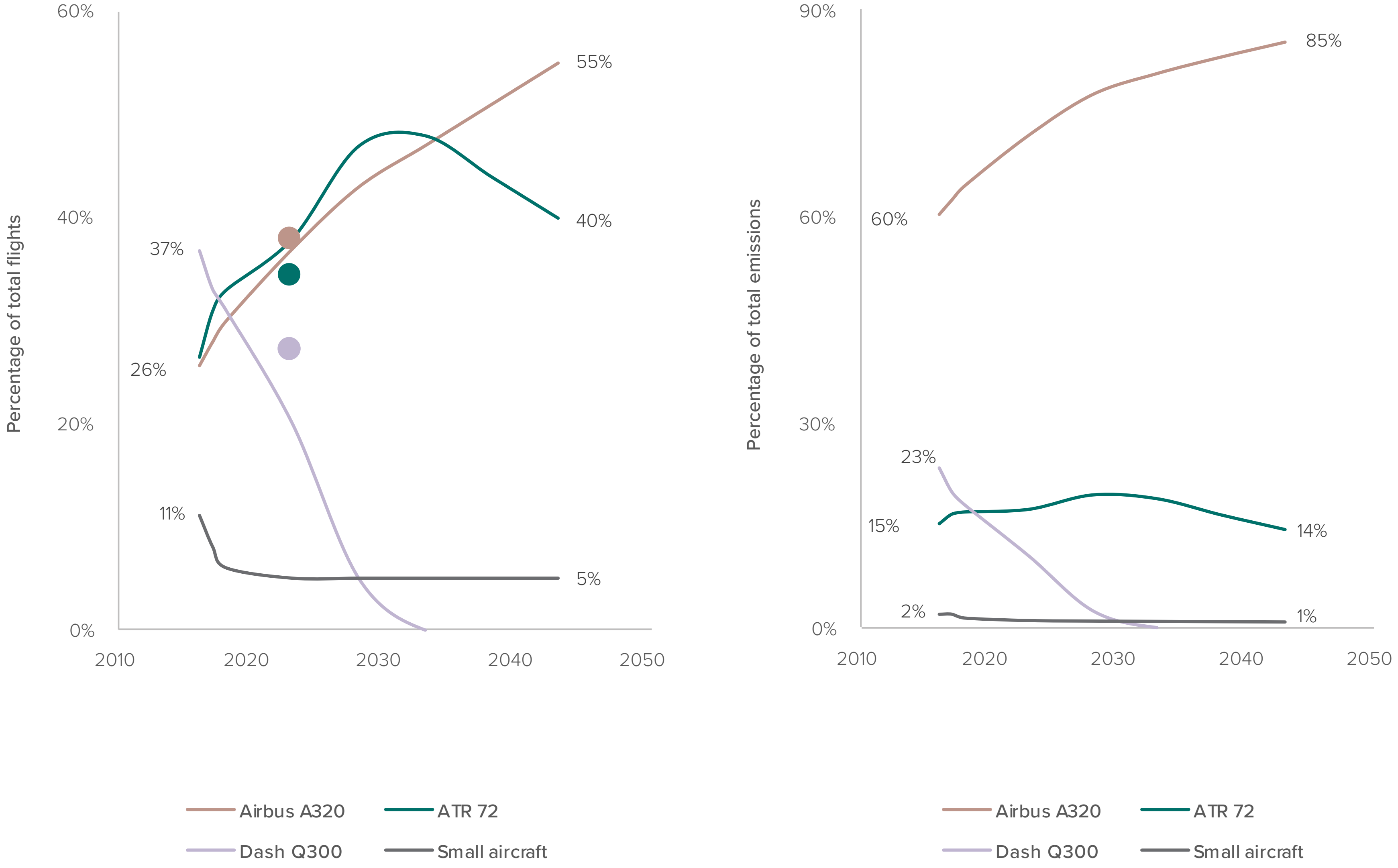


Figure 2: Average flight distance per aircraft in the domestic fleet.

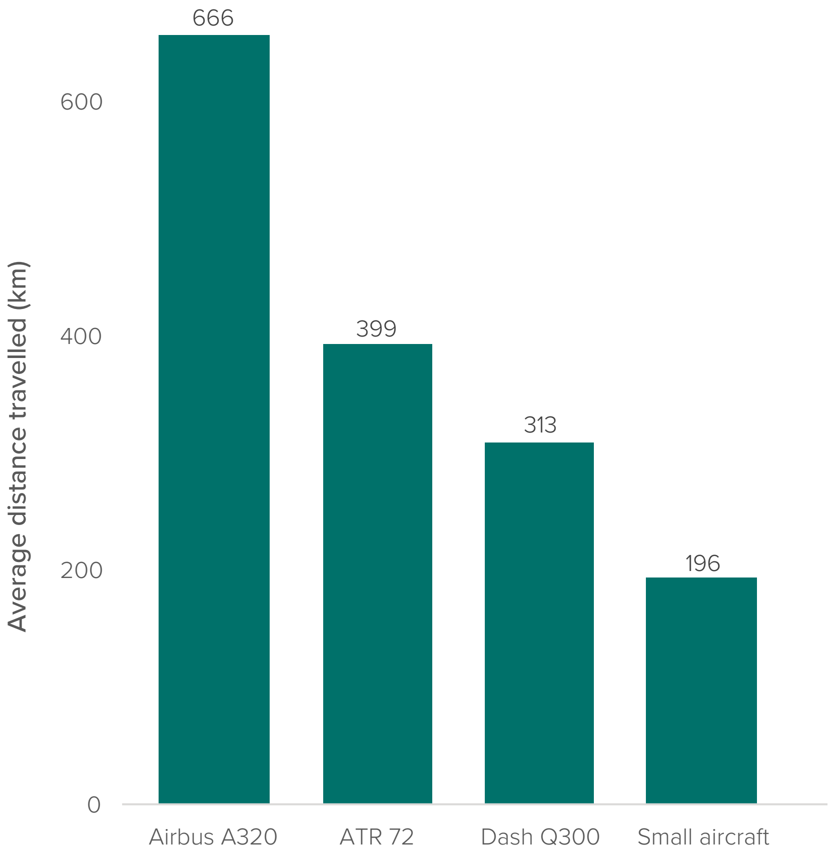
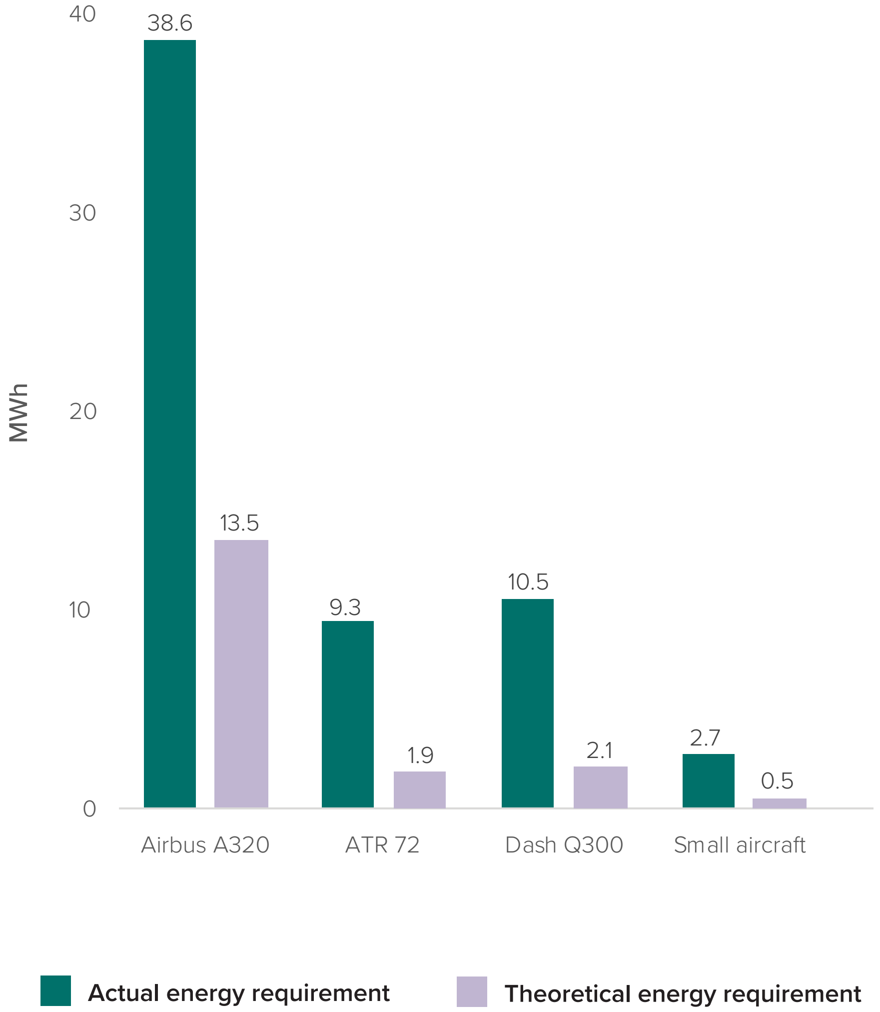


Figure 3: Actual (left) and theoretical (right) energy requirement per average domestic flight.



Emissions reduction

Using the theoretical energy usage per flight, combined with the energy to propulsion efficiencies (an average of 30% for Jet A and sustainable aviation fuel, 45% for hydrogen – noting that this is for fuel cell technology rather than hydrogen combustion; the latter will be considered in subsequent sections – and 80% for batteries)[9,10] and the relevant specific energy, the total energy carrier demand for each given emissions reduction option can be determined and compared to Jet A.

This measurement alone is not particularly useful as it gives no context into the emissions reduction (if any) achieved by the various decarbonisation options. Table 1 details the relative range of 'well-to-wake' lifecycle emissions of each energy carrier across three different bases. SAF has been listed four times as lifecycle emissions vary significantly depending upon feedstock and production process – the main feedstock/process combinations are Hydroprocessed Esters and Fatty Acids (HEFA), Fischer-Tropsch (FT; which includes the production of e-kerosene or eSAF from hydrogen and direct air-captured CO_2) and Alcohol-to-Jet (ATJ):

Table 1: Energy carrier emissions intensity

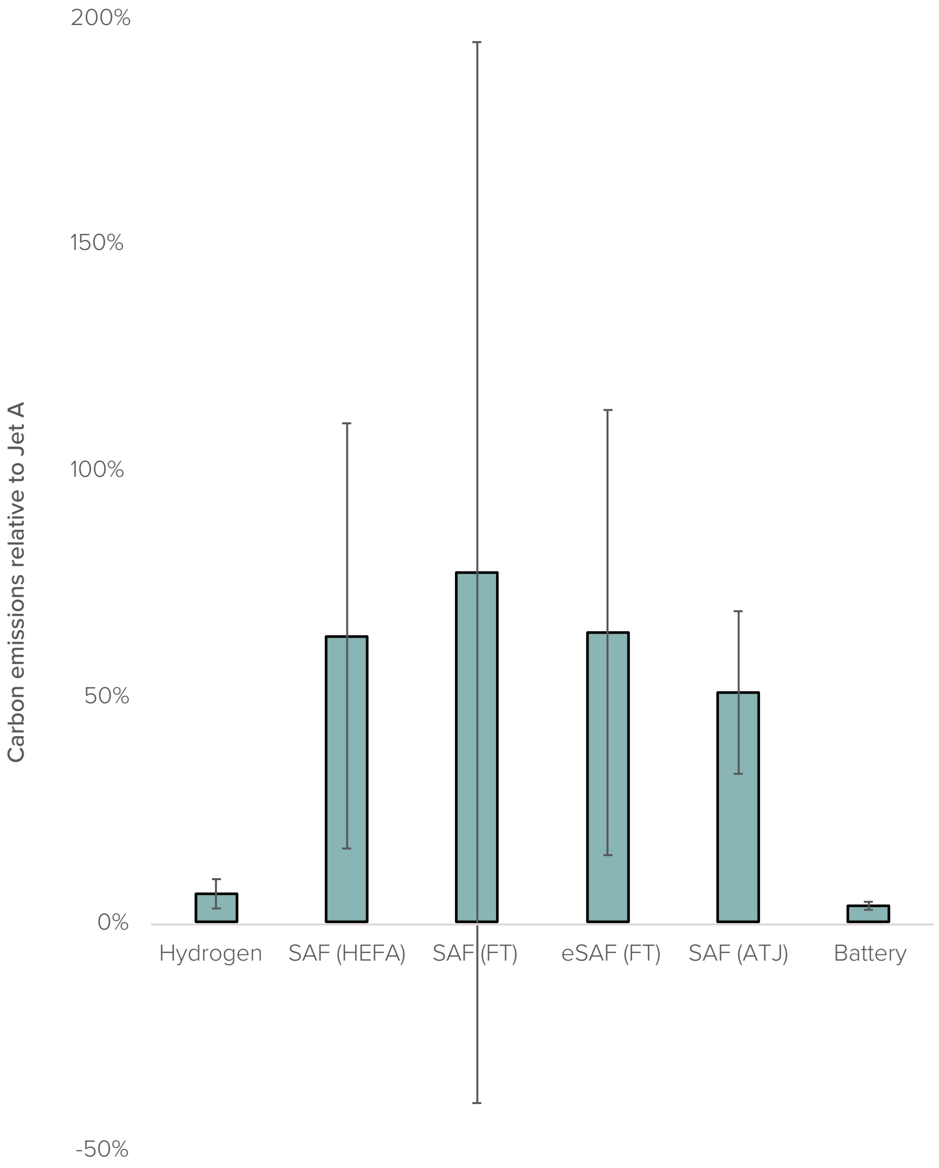
CO_2 emissions	**kg CO_2e/kg**		**kg CO_2e/MJ**		**kg CO_2e/kWh**	
Emissions range	*Lower*	*Upper*	*Lower*	*Upper*	*Lower*	*Upper*
Jet A[11]	3.87	3.87	0.089	0.089	0.320	0.320
Battery [12,13*]	0.005	0.009	0.006	0.010	0.021	0.037
Hydrogen[14]	0.30	1.00	0.003	0.008	0.009	0.030
SAF (HEFA)[15]	0.62	4.26	0.014	0.098	0.051	0.352
SAF (FT)[15]	-1.55	7.53	-0.036	0.173	-0.128	0.623
eSAF (FT)[15#]	0.57	4.37	0.013	0.101	0.047	0.362
SAF (ATJ)[15]	1.26	2.65	0.029	0.061	0.104	0.220

* assuming a battery lifetime of 3,000 cycles.

\# the upper emissions intensity assumes the use of grid electricity (0.074 kg CO_2e/kWh) and a 20% conversion efficiency.[16,17]

Upon utilising the emission intensity factors, the total level of emissions reduction for a given energy carrier can be determined and the results are presented in Figure 4, relative to Jet A (which has a value of 100%). Green hydrogen, made via electrolysis of water with electricity derived from either wind or solar, will result in a domestic aviation emissions reduction between 90-97% if used to decarbonise the entire domestic fleet. Batteries will result in a similar reduction in emissions (96-98%, with an assumed lifetime of 3,000 cycles), however SAF, depending upon the feedstock and production method, could either significantly reduce or increase domestic aviation emissions. If 100% biological solid waste (FT) were used as a feedstock, emissions would in fact be negative (due to a reduction in landfill emissions) if used across the entire fleet. By comparison, using 100% non-biological solid waste (FT) would increase emissions by 94%. Considering all potential feedstocks, the average emissions reduction achieved by SAF is 63% for HEFA, 77% for FT and 51% for ATJ respectively. In regard to eSAF, if using green hydrogen and renewable electricity, emissions would reduce 85%. If using electricity from today's grid, eSAF emissions would be 13% greater than Jet A.

Figure 4: Relative emissions of domestic aviation decarbonisation options



Weight and volume constraints

Crucial to aviation, reducing the emissions of the domestic fleet requires a propulsion method which complies with both aircraft take-off and landing weights, any legal fuel reserve requirements in the case of flight diversion or airport loitering, as well as any volumetric requirements given any additional bulk will influence flight dynamics.

The energy carrier specifications relevant to understanding this problem are provided in Table 2. The relevant aircraft specifications are provided in Appendix B, however it is worth noting that these specifications are configured for Jet A fuel propulsion. The engines will remain mostly the same, but for energy carriers other than SAF (which is a drop-in fuel), there are likely other complexities to consider (i.e. power delivery/torque curves, weight distribution etc.). This however goes beyond the scope of this report and a direct comparison to the baseline technology should provide a reasonable viability estimate. An important inclusion in this analysis is differentiating between hydrogen fuel cell technology and hydrogen combustion. It is expected that turboprop aircraft (ATR 72/Dash Q300) will utilise fuel cells to create electricity to drive the engines, whereas turbofans, such as A320s, will burn hydrogen to create thrust.[10,18] Fuel cells have a higher efficiency (45%) than turbofan combustion (35%), and this has been accounted for in the subsequent analyses.

Table 2: Energy carrier properties

	Specific energy	Volumetric density
	MJ/kg	*kg/m³*
Jet A	43.5	800
Battery	0.9	2610
Hydrogen*	120	71
SAF	43.5	800

*liquid at -253°C and 1 atmosphere

As previously noted, SAF is very much like-for-like with Jet A, however batteries and hydrogen are significantly different in terms of both the weight and volume required to deliver the same amount of energy. Batteries are significantly denser in terms of weight by volume i.e. more can fit into a smaller space (which is positive considering a scenario such as this where volume is limited), however a significantly higher weight of batteries is required to deliver the same energy when compared to the other energy carriers. Hydrogen is more energy dense and significantly lighter on a volumetric basis than the other alternatives, however this will result in requiring larger volumes to achieve the same level of work. Other complications with hydrogen include the need for it to be stored in the fuselage rather than in the wings, as well as cryogenic systems to store it as a liquid. The most recent mass ratios for liquid hydrogen propulsion systems is 51% hydrogen: 49% ancillaries, however a more conservative hydrogen mass fraction of 35% has been selected to align with similar studies.[18,19] Batteries also require similar ancillaries (such as cooling systems) and these will inflate both the volume and weight required for these options. This ancillary inflation has been accounted for in the hydrogen calculations, but has not in the battery calculations.

In addition to the energy carrier volumes required to travel from A to B, there are minimum legal fuel reserves set by the Civil Aviation Authority of New Zealand in the case a diversion is required or there is an extended loitering time before landing. For turbine-powered aeroplanes (i.e. A320), the minimum requirement is an additional fuel volume sufficient to divert to a suitable alternate aerodrome plus 30 minutes at holding consumption rate at 1,500 feet; this increases to 45 minutes for non-turbine powered aircraft (ATR 72, Dash Q300).[20] In both cases, when assuming an alternative airport is a maximum of 100 km away and non-turbine and turbine powered aircraft are capable of loiter velocities of 80 m/s and 120 m/s respectively (where these estimates are in line with similar studies),[21] the total additional energy carrier reserves must be equivalent to 316 km of travel distance.

Weight loading

Utilising the above energy carrier information and the aircraft specifications, the average take-off and landing weights with respect to the average flight taken by an aircraft in the domestic fleet could be determined (assuming an average passenger weight of 100 kg).[22] Results from this analysis are shown in Figure 5, with the relative weight proportions of an Airbus A320 powered by each technology shown in Figure 6.

As one would expect, Jet A and SAF have equivalent weights with a loading range between 83% and 97% for take-off and 87% and 95% for landing when compared to the aircraft maximums. Despite hydrogen's light weight and high specific energy, the ancillaries required result in a very similar loading range of 83-92% for take-off and 83-93% for landing. Aircraft powered by batteries, in all cases, are significantly over the design take-off (179-221%) and landing (182-235%) weights without accounting for any ancillaries.

The reason for this is immediately identifiable as the higher specific energy liquids only contribute between 4-11% towards the total aircraft weight, whereas the batteries contribute 50-61%. It is also noteworthy that the take-off and landing weight of a battery-electric aircraft is the same, whereas liquid energy carriers are utilised for propulsion and, as a result, the aircraft weight decreases with distance travelled. This is a significant design assumption when considering aircraft landing gear.[23]

From the analysis presented in Figure 7, in order for a battery-electric aircraft to achieve parity with the design landing weights, the battery energy is required to increase between eight and sixteen times, assuming average flight distances. An eight times increase will enable the average small plane flight (5% of cumulative 2043 flights) to meet these design requirements; a sixteen times increase is required for the remainder of typical 2043 flights. This increase is equivalent to a battery with a specific energy of 14.4 MJ/kg or 4,000 Wh/kg – this is the theoretical maximum specific energy of a lithium oxygen battery, which has among the highest theoretical electrochemical battery energy densities. Importantly, the realistic specific energy for such batteries is expected to be approximately half that (≈2,200 Wh/kg), reducing with increasing battery cycling.[24]

Figure 5: Average take-off (top) and landing (bottom) weights with respect to aircraft maximum. TO: Take-off; LD: Landing. These values are associated with the leg-based distances provided in Figure 2 plus the minimum fuel requirements.

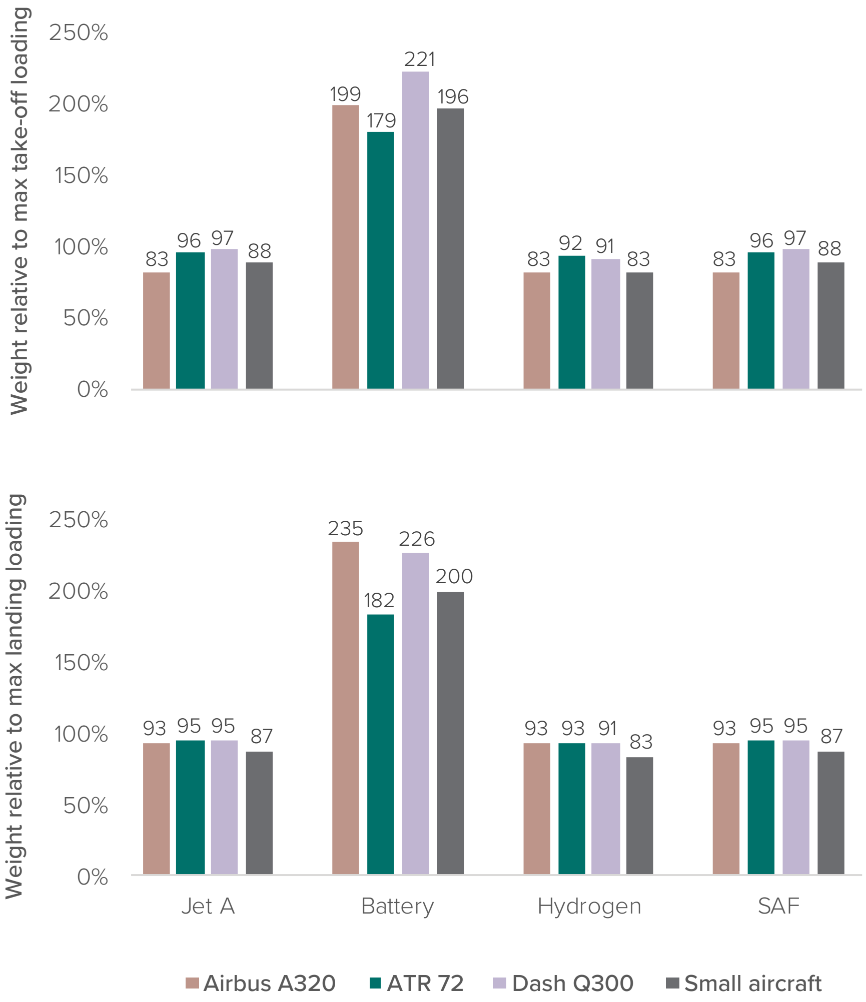


Figure 6: Relative percentage of weight components contributing to the total mass of an Airbus A320 for a given energy carrier.

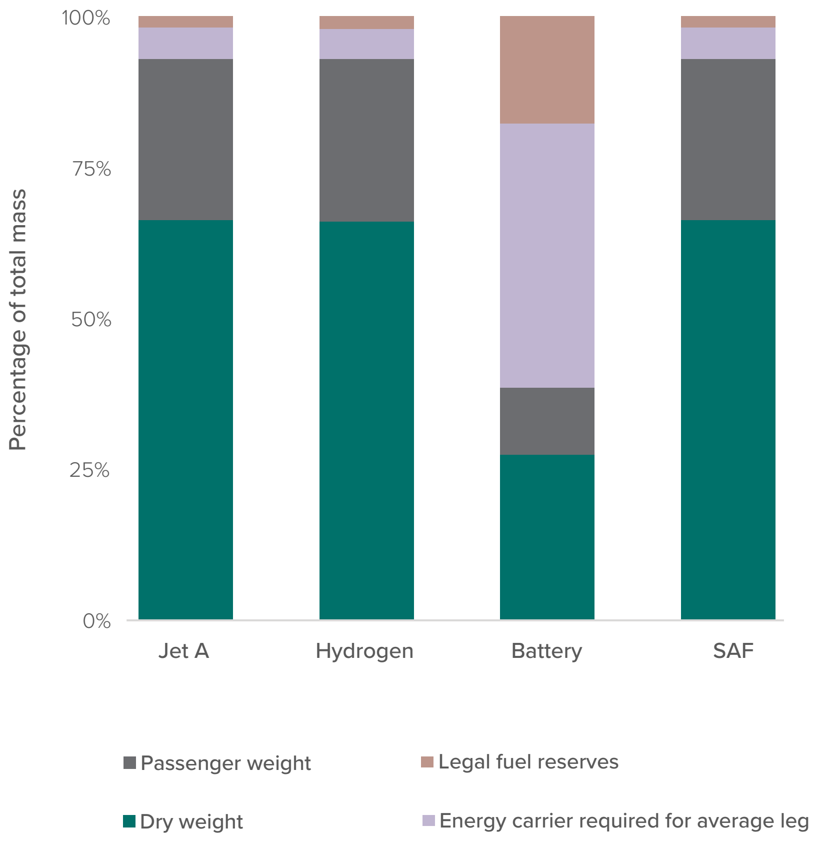
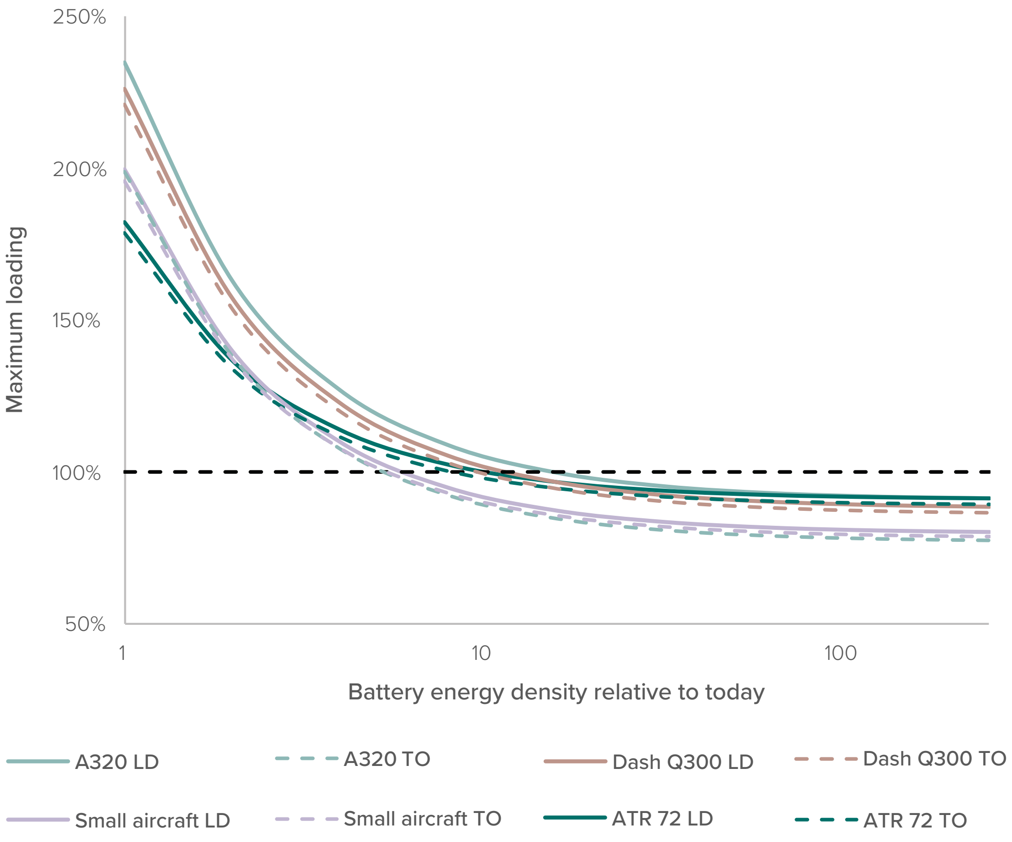


Figure 7: Average aircraft loading relative to design maximum as a function of increasing battery specific energy. TO: Take-off; LD: Landing.

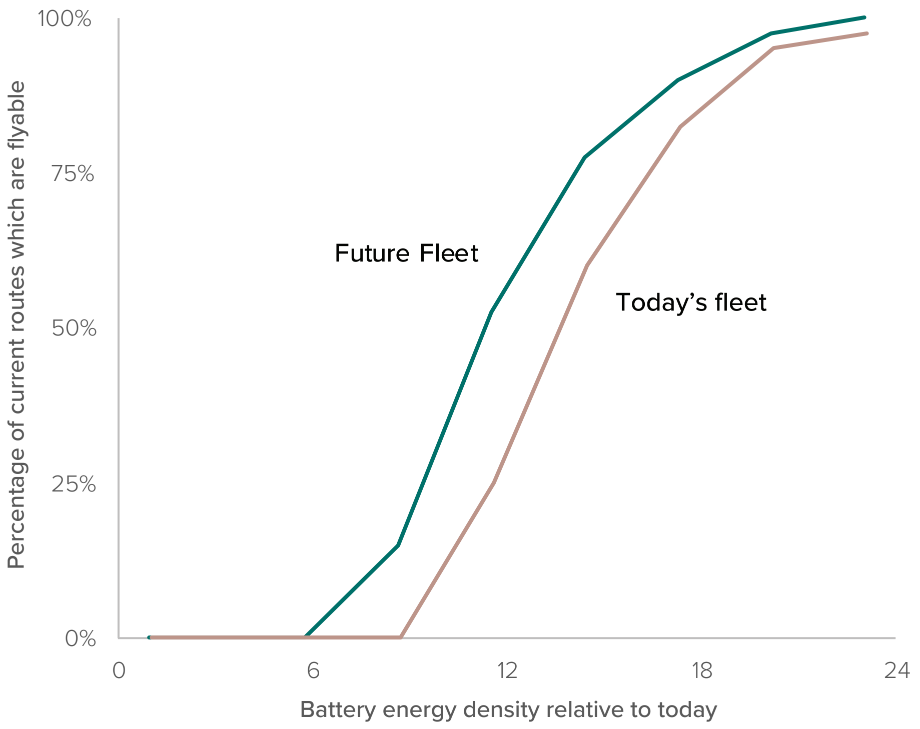


Something important to note though is that the above analysis is essentially asking the question “what is the battery specific energy required to fly the average route distance in a given aircraft?” without considering the fact that there is great variance in the distances flown by these planes in New Zealand due to the varying flight routes.

If we consider the current routes flown by Air New Zealand (see Appendix C), the national carrier who has a large majority in the domestic market, the length of routes flown today by a given airplane type varies by well over 50%. For example, the routes flown by a A320 (average of 666 km) range from 302 km to 1,183 km; similarly, Dash Q300 (average of 313 km) routes range from 74 km to 767 km. Due to this, the previous analysis considering an average distance basis will overpredict the battery specific energy required for short flights and underpredict the specific energy required for longer flights. An analysis taking into account the relevant routes travelled by a given airplane type is presented in Figure 8 for both today’s fleet and the predicted future fleet.

Upon assessment, even if battery energy densities were to increase eight times (to a value of 2,000 Wh/kg), we find that no routes with today’s fleet and only 15% of routes with the future fleet could be conducted using battery-electric technology. This increases to 25% and 53% of routes for energy densities of 3,000 Wh/kg. However, in both cases, the longest flights (which represent 35% of routes with today’s fleet and 12% of routes with the future fleet) require battery energy densities of over 4,000 Wh/kg, and in some cases, up to 6,000 Wh/kg (which is well over the theoretical maximum specific energy of an electrochemical battery).

Figure 8: Percentage of routes which are flyable against battery specific energy relative to today. Today’s fleet is based off current Air New Zealand operations (see Appendix C).*



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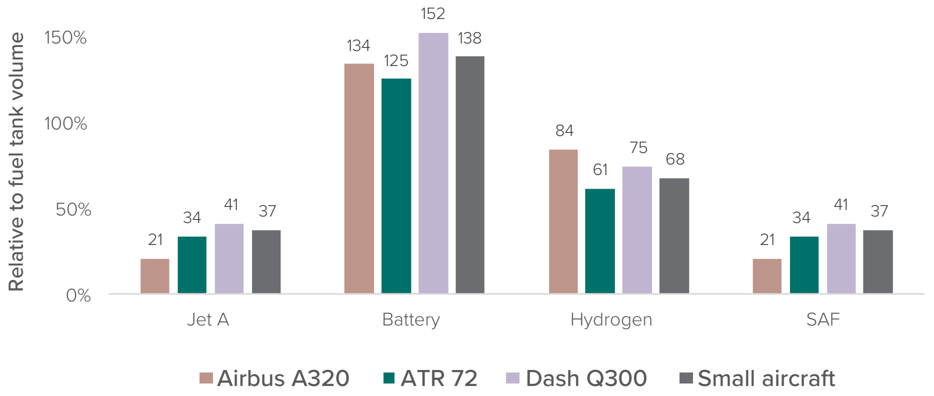
* The future fleet, aligning with fleet projections, assumes all ATR 72’s in today’s fleet have been replaced with A320s and all Dash Q300 models have been replaced with ATR 72s.

Energy carrier volume

The required energy carrier volume was also determined and benchmarked using the aircraft's fuel tank size (see Figure 9). Jet fuel and SAF typically only require the fuel tank to be 20-40% full on an average flight across the domestic network and this seems reasonable when considering the maximum aircraft distances relative to those travelled in New Zealand. This also makes sense when considered from a mass perspective as a full Jet A fuel tank in an A320 (27.2 m^3) will increase take-off loading approximately 100% of the maximum allowable value. In contrast, due to the low volumetric density of hydrogen, the average flight on the domestic network will require 61-84% of the available fuel tank volume to get from A to B. Although this presents an issue for longer distance flights, this seems reasonable when considering the New Zealand domestic network, as long as there is capability to refuel at the destination (for comparison, a Jet A aircraft would only need to be refueled every three to five legs due to not having the same volumetric constraint). Again, due to low specific energy, batteries would require up to one and a half times the current tank volume to provide the energy required for a typical domestic flight (between 125-152%). However, as detailed in Figure 7, without significant increases in specific energy these battery-electric aircraft, figuratively, will not get off the ground due to weight restrictions.

Figure 9: Energy carrier volume required with respect to aircraft fuel tank maximum.



Despite hydrogen seemingly meeting the required volume requirements, liquid hydrogen cannot be stored in the wings like Jet A and needs to be stored in the fuselage.[10] Work from the International Council on Clean Transportation (ICCT) estimates that two 0.47 m^3 liquid hydrogen tanks use the same volume in the fuselage as a row of 4 seats in both an ATR 72 and a Dash Q300, giving approximately 288 and 202 kilometres of flight range (noting 316 km is the legal minimum before accounting for leg distance). Although there may be a small amount of unoccupied space in the rear of each airplane's cabin, it is highly unlikely that today's fleet could utilise hydrogen whilst maintaining the same passenger capacity and flight range. However, future projections estimate that larger planes will be used for the same routes.

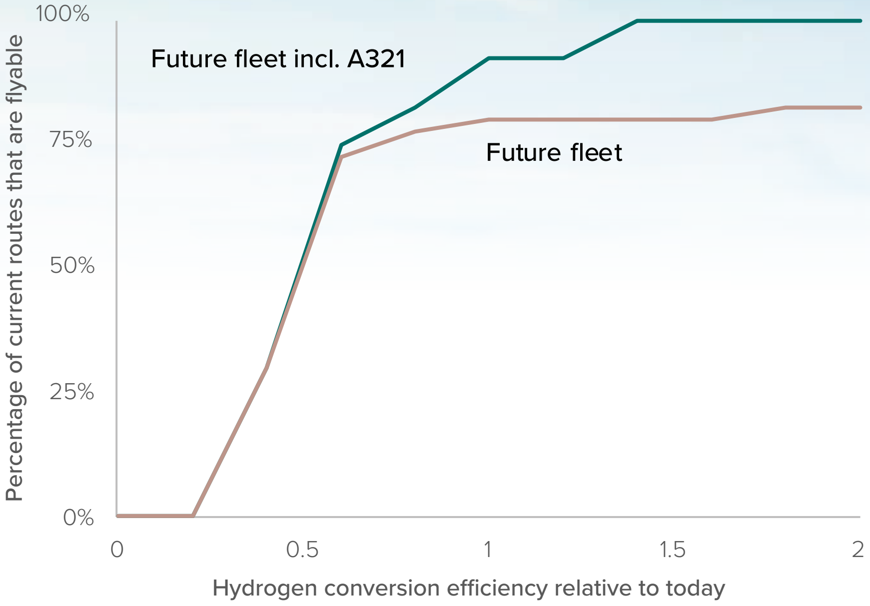
As per the future scenario detailed in Appendix C, in New Zealand's future domestic fleet, all ATR 72's will be replaced with A320s and all Dash Q300 models will be replaced with ATR 72s. With an estimated seat pitch of 85 cm,[25] this change, if we assume passenger numbers remain reasonably constant, will result in potentially empty fuselage space of 7.3 m on previous Dash Q300 routes and 17.95 m on previous ATR 72 routes.[ii] In addition to greater fuselage space, new Airbus A320 routes, due to significantly greater fuselage diameters (3.7m compared to 2.57 m in an ATR 72), are assumed to be able to place four 0.47 m^3 liquid hydrogen tanks per row of 6 seats. Using these assumptions, the percentage of flyable routes across the domestic network are presented in Figure 10 against hydrogen energy conversion efficiency.

[ii] Dash Q300 has a total of 50 seats; 4 seats per row. ATR 72 has a total of 68 seats; 4 seats per row. Airbus A320 has 171 seats; 6 seats per row.

Using today's overall efficiency values of 45% for hydrogen fuel cells in the ATR 72 and 35% for the turbofan model,[9] 80% of routes on the domestic network could be flown by the future fleet using hydrogen. Although the thermodynamics are not plausible, even if these overall efficiencies were doubled (i.e. 90% and 70%), still only 33 out of the 40 routes (83%) could be flown, with the remaining 17% being associated with the original A320 flights where no additional fuselage space was made available through fleet updates.[iii]

In recent years, Air New Zealand has begun introducing 217-seater Airbus A321 aircraft into the domestic fleet.[26] If it is assumed that all original A320 routes are replaced with A321 planes, the entire domestic network could utilise hydrogen (whilst maintaining the same passenger capacity as today) if a 63% turboprop efficiency and 49% turbofan efficiency were achievable (noting that these values do align with ICCT's ambitious fuel cell scenario and the industry expectation of aircraft being 40% more efficient by 2050 compared to a 2019 baseline).[10,27] However, the Ministry of Transport expect that passenger numbers are likely to increase and if green hydrogen is prioritised to decarbonise domestic aviation, new planes designed specifically for liquid hydrogen storage (currently under-development) will likely be purchased rather than retrofitting liquid hydrogen tanks to existing Jet A-fuelled planes.[28,29]

Figure 10: Percentage of routes which are flyable against hydrogen energy conversion efficiency relative to today. The future fleet is based off projected Air New Zealand operations (see Appendix C).*



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iii It is estimated that only 3.29m of fuselage space would be available for hydrogen storage in an A320 if accommodating 171 passengers. This is around half the requirement for the shortest current A320 route in NZ.

* The future fleet, including A321s, assumes all A320's in today's fleet have been replaced with A321s whilst the other aircraft in the future fleet remain the same.

Feedstock demand

The final consideration is whether there is appropriate supply to meet demand if a given energy carrier was utilised to reduce the emissions of domestic aviation.

This analysis has been split into electricity demand (considering all options require this to provide the energy) and resource demand, specifically water for hydrogen electrolysis (to be used either for liquid hydrogen or eSAF) and both waste woody biomass and used cooking oil for SAF production (FT/HEFA).

Electricity demand

Figure 11 details the relative electricity demand for the use of green hydrogen, SAF and electrochemical batteries in decarbonising domestic aviation in New Zealand.

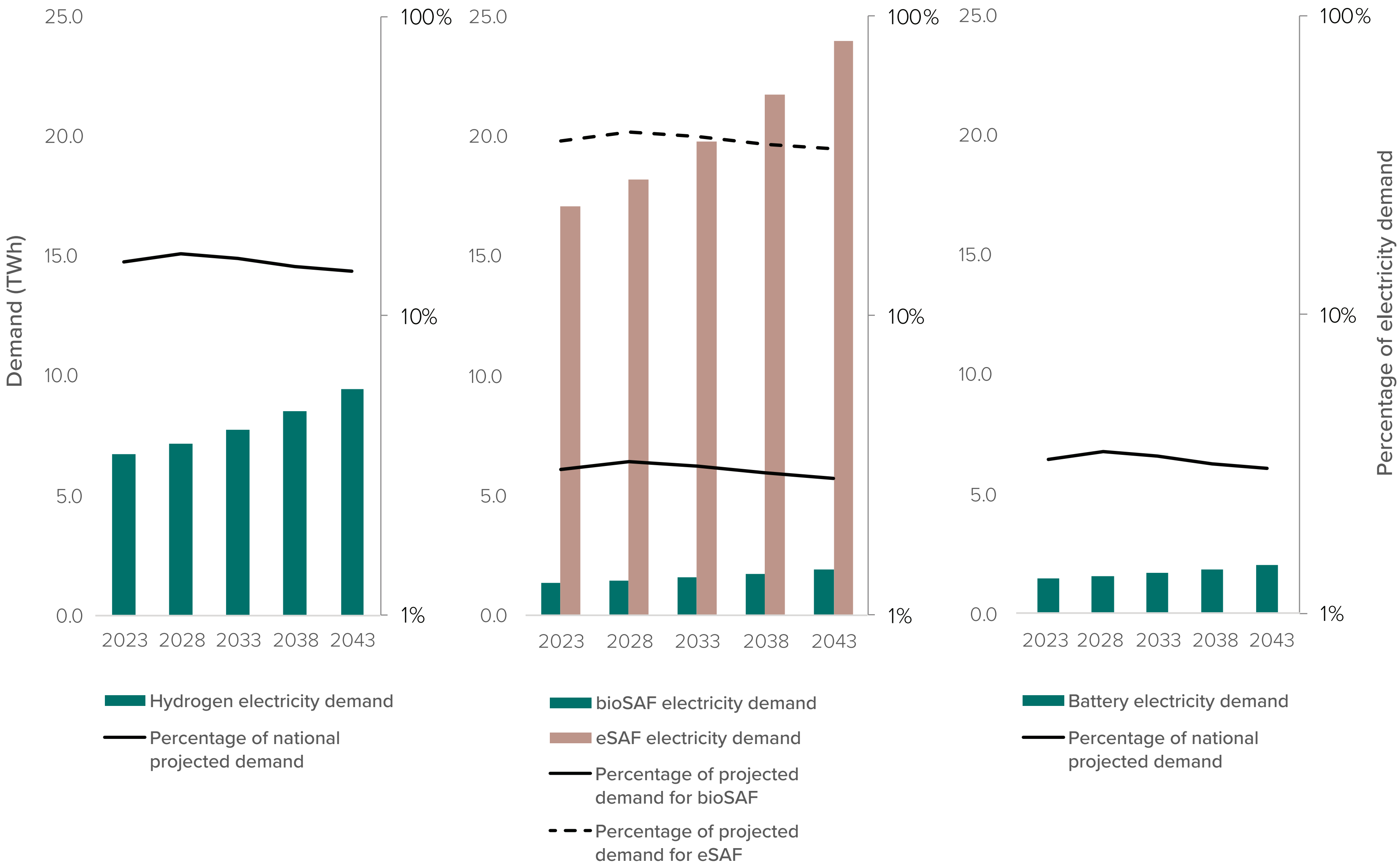
A recent report from EY,[30] commissioned by the Ministry of Business, Innovation and Employment, on the future hydrogen economy stated an electricity demand of approximately 49 kWh per kg H_2.[iv] Based upon this, total domestic aviation demand by 2043 (assuming 100% uptake) is estimated to be 7.2 TWh (or 147 kt H_2),[v] which is equivalent to 10.8% of the expected national usage.[31] If the energy required to liquify the hydrogen is included, this increases to 9.4 TWh and 14.1%.[32] These values are large, but it is expected that additional renewable developments such as Kōwhai Park solar farm near Christchurch Airport will be built to reduce this proportion/meet aviation demand.[33] This however will be no straightforward task as the equivalent of 32 Kōwhai Parks (0.29 TWh/year) would have to be built by 2043 to decarbonise domestic aviation using liquid hydrogen.[34]

Electricity demand to produce biomass-based SAF (bioSAF) via the Fischer-Tropsch process is comparatively very small to abate the emissions of domestic aviation (1.9 TWh; 2.9% of demand),[35] however, as described in the subsequent section, the domestic supply of waste biomass is constrained, and like SAF emissions, the energy demand to produce the fuel is very much associated with the feedstock used. For example, if considering the power-to-SAF pathway for domestic aviation (where there are no typical feedstock constraints due to being produced from effectively water and air), eSAF would require 24.0 TWh of electricity to meet domestic aviation's energy demand in 2043. This is due to the fact that hydrogen must first be produced via electrolysis of water and carbon dioxide must be forcefully separated from the atmosphere before being able to produce a jet fuel alternative (as well as a number of other byproducts).[17] As a result, reducing domestic aviation emissions using eSAF would require ten times the electricity of biologically-derived SAF and twice the electricity demand if using hydrogen as the energy carrier.

[iv] This assumes an electrolysis efficiency of 68%.

[v] EY assumed 55% of domestic aviation is utilising kt H_2 via fuel cell and 20% via combustion/battery hybrid. Their base case expects 30 kt by 2050, accelerated uptake expects 71 kt. Extrapolating to 100% of the fleet is 95 kt. The New Zealand Hydrogen Aviation Consortium estimate 100 kt and 6.7 TWh by 2050; these are the same values determined in this study for 100% of demand as of 2023 (including liquification energy requirements).

Figure 11: Electricity demand if domestic aviation emissions were reduced using green hydrogen (left), bioSAF/eSAF (middle) or electrochemical batteries (right). Values assume 100% uptake of projected demand.



Emissions reduction via batteries would only require 2.0 TWh or 3.1% of the expected 2043 national usage. This is comparable to bioSAF and more than four times more efficient than liquid hydrogen and eSAF, but as mentioned previously, the major caveat at present is that the specific energy of battery technology must improve by orders of magnitude for large aviation applications.

Resource demand

Figure 12 details the supply and demand of raw materials required for hydrogen and SAF. Battery supply and demand has not been included as categorising relative demand is difficult due to the varying industries where battery storage is needed.

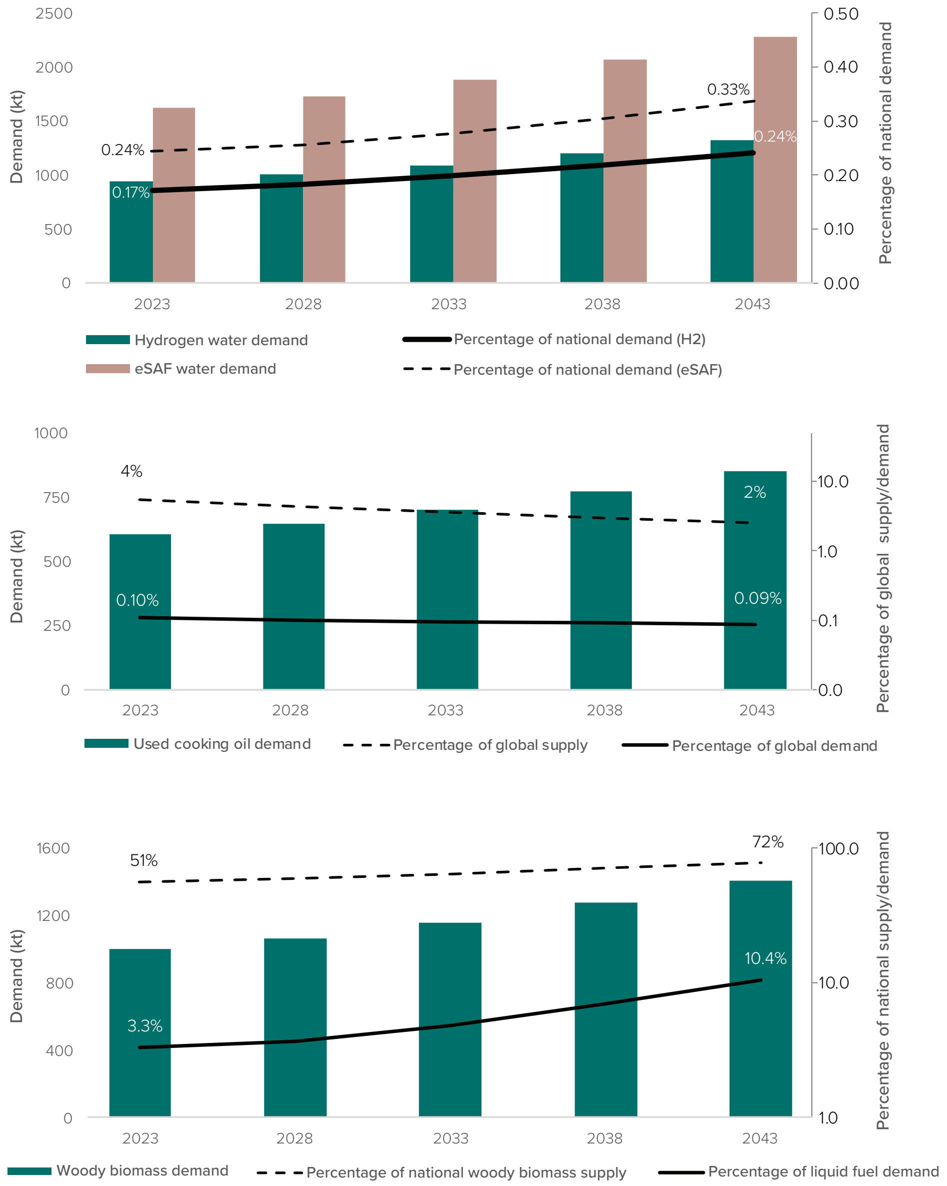
Other than renewable energy and an electrolyser (demand has also not been determined for the same reason as batteries), the key ingredient to produce hydrogen is water - 9 kg of pure water is required per 1 kg of hydrogen. When considering the total amount of hydrogen required to abate domestic aviation emissions, this leads to a total annual consumption of 1,324 kt by 2043. By comparison, in 2022 New Zealand consumed an estimated 550,000 kt across industry, residential and pipeline losses.[36] Based upon this value, hydrogen production for domestic aviation would only utilise 0.24% of typical annual consumption.

In regard to SAF, among a selection of others, two potential biological feedstocks to decarbonise are used cooking oil or waste woody biomass. These feedstocks have been specifically selected due to achieving a similar emissions reduction to green hydrogen. The third option for SAF with comparable emissions is eSAF, produced using green hydrogen and direct air-captured carbon dioxide.

Using the HEFA process, it has been estimated that 2.1 kg of used cooking oil can produce 1 kg of SAF,[37] meaning 852 kt will be required to decarbonise New Zealand domestic aviation in 2043 (based upon a total SAF demand of 403 kt). Current global supply for used cooking oil is approximately 14,000 kt, with a total future potential of 57,000 kt.[38] This volume is sufficient to replace jet fuel across New Zealand's domestic network, however it isn't an optimal solution as this would require using 2% of the global supply to decarbonise approximately 0.1% of global demand.[39]

Conversely, physical resources to produce eSAF are reasonably plentiful in New Zealand due to effectively only requiring water (hydrogen), air (carbon dioxide) and power for the power-to-liquids process. Approximately 3.6 kg of CO_2 and 4.5 kg of water is required per kg of hydrocarbons produced.[40] This results in overall demand of 1,461 kt of CO_2 and 1,826 kt of water to meet domestic aviation fuel demand by 2043. With projections that global direct air-capture technologies will produce 98,000 kt of CO_2 by 2050, the former will require approximately 1.5% of global supply.[41] In regard to water, eSAF for domestic aviation will only require 0.33% of national water demand (noting that this is a 40% increase compared to using hydrogen directly).

Figure 12: Resource supply and demand. Water for hydrogen (top); used cooking oil (middle) and woody biomass for SAF (bottom).



When considering the alternative Fischer-Tropsch approach, the conversion of woody biomass (as proposed in the Forestry and Wood Processing Industry Transformation Plan), the estimated conversion rate is 3.5 kg of dry biomass per kg SAF.[42] This leads to a 2043 dry waste woody biomass demand of 1,405 kt for domestic aviation. An analysis by Scion has estimated an annual domestic supply of waste woody biomass up until 2050 of 3,900 kt (excluding any materials that currently have a market).[43] This value is for 'green' biomass, with an approximate moisture content of 50% which would be removed during processing, meaning SAF for domestic aviation would utilise 72% of New Zealand's dry waste woody biomass supply despite only accounting for 10% of liquid fuel demand (projected 2043 liquid fuel demand of 3,883 kt according to the Climate Change Commission's demonstration pathway).[44] If other markets are deprioritised (increasing annual green supply to 7,600 kt), domestic aviation's share of the dry waste woody biomass supply would decrease to 37%.

Although, in theory, there is sufficient demand to meet supply, consideration should be given to whether using waste woody biomass to decarbonise domestic aviation is the most appropriate use for this feedstock or whether it should be used to reduce the emissions of other hard-to-abate sectors, especially those with no obvious technical alternatives. One example hard-to-abate sector is international aviation – unlike domestic flights (of the order of 1,000 km) where utilising hydrogen in the fuselage is possible, 10,000 kms of range (e.g. Auckland to San Francisco) would require over 250 m^3 of hydrogen. If we conservatively estimate 10 m^3 of liquid hydrogen per metre of fuselage on an A380 (the value used previously for a A320 was 2.2 m^3/m), nearly half the cabin would be taken up by fuel tanks (cabin length of 50.7 m) and passenger numbers would be significantly reduced. The electricity required to abate New Zealand's international aviation emissions using green hydrogen would also require 49% of projected 2043 supply – this is equivalent to 32 TWh (or 75% of the current national electricity demand).

Conversely, if decarbonised using waste woody biomass, international aviation (which will account for approximately 36% of New Zealand's 2043 liquid fuel demand),[44] will require 128% of the national waste woody biomass supply, assuming other markets are deprioritised. Abating all New Zealand aviation emissions (domestic and international) with biomass-derived SAF would require the entire annual supply of waste woody biomass plus an additional 5,000 kt of imported 'green' biomass each year. Alternatively, SAF could be imported from overseas to make up the difference, but in that scenario control over the total emissions associated with the fuel may not be guaranteed.

Importantly, if bioSAF is prioritised for both domestic and international aviation, emissions from the remaining 54% of liquid fuel demand would need to be reduced using other feedstocks (assuming an *improve* approach is taken). This remaining portion includes a 12.7 PJ (or 292 kt) liquid fuel requirement for international and domestic shipping where battery-electric or green hydrogen alternatives are not likely decarbonisation options. Fischer-Tropsch based biofuels will be required to reduce shipping emissions in New Zealand and this sector will require 2,020 kt of 'green' biomass in 2043 to do so – domestic aviation will require the same amount plus an additional 790 kt of green waste woody biomass (using an additional 10% of total supply) to decarbonise, despite having alternative abatement options.

Economics

For the purposes of this report, where the technical viability of different emissions reduction options are being considered for domestic aviation, trying to understand the full economic viability of each has been excluded from the scope.

This is due to the fact that despite having a reasonably good understanding of the potential costs associated with each given option on a particular levelised basis (i.e. 2020 costs: liquid hydrogen, $200/MWh; battery electric, $150/MWh; SAF, $225/MWh, eSAF, $450/MWh. Expected 2050 costs: liquid hydrogen, $100/MWh; battery electric, $120/MWh; SAF, $175/MWh, eSAF, $125/MWh.),[27] the actual total levelised cost associated with each option is dependent upon other cost factors not included in the typical calculations. These factors include transmission and other airport infrastructure upgrades, as well as costs associated with purchasing new planes and other related technology. These costs are difficult to estimate without a thorough study of both the national electricity grid (given upgrade costs will vary across the country) and the specific build requirements of non-Jet A powered planes and airports.

Discussion and concluding remarks

A technical analysis has been conducted on three *improve* options to reduce domestic aviation emissions in New Zealand. These options included green hydrogen, sustainable aviation fuel (SAF) and electrochemical batteries.

Green hydrogen, produced through water electrolysis and renewable energy, is a viable technical option to decarbonise domestic aviation as potential emissions reduction is significant (between 90-97%), fueling aircraft with hydrogen will meet the relevant mass constraints, and both water and renewable energy are plentiful in New Zealand. The key hurdle to overcome is volume constraints in regard to storing liquid hydrogen in the fuselage of planes, potentially slightly reducing passenger numbers. This, however, is expected to be overcome through alternate aircraft designs like those currently being circulated by Airbus.[29] It is crucial however to note that these aircraft are only early into the development phase, with *an expectation* that commercial flights by these designs will begin in 2035. Some innovators, such as ZeroAvia and Universal Hydrogen,[45,46] have begun test flights for small planes retrofitted with hydrogen, but for entirely new aircraft, this timeframe is threatened by the fact that as a new technology, it will need to be thoroughly tested and proven in order to cross the commercialisation valley of death (before even considering the other issues associated with an aviation sector using hydrogen as an energy carrier).

Alongside hydrogen aircraft production, if green hydrogen is prioritised to decarbonise domestic aviation, significant infrastructure will need to be developed at airports throughout the country in order to produce a sufficient amount of liquid hydrogen to keep up with demand and refuel the fleet. Appropriate regulations will also need to be in place to ensure that a hydrogen-based domestic aviation sector can be operated both safely and efficiently.

SAF is likely the easiest to implement due to being a drop-in fuel (and is already in use commercially today e.g. the first transatlantic flight on used cooking oil-derived SAF flew in November 2023),[49] but emissions reduction is fully dependent upon the feedstock used to produce it. Through the HEFA process, used cooking oil provides similar emissions reduction to green hydrogen, but even when considering the potential future global supply, New Zealand's domestic aviation sector would require a supply 20 times larger than its share of global demand to fully decarbonise.

eSAF does not have these same supply-side constraints due to being a product of essentially air and water, however, it is reliant on the commercialisation of early-stage direct air-capture technology and the overbuild of renewables to produce the very large amounts of electricity required to meet demand. Owners of Marsden Point, Channel Infrastructure, and Fortescue Future Industries are currently investigating the feasibility of an eSAF plant in Whangārei,[50] however this study suggests that the electricity required to produce eSAF is more than double that required to produce liquid hydrogen and ten times more than required to produce bioSAF.

If considering the national supply of waste woody biomass, 72% of the supply could abate domestic aviation emissions, however this makes up only 10% of the projected 2043 demand for liquid fuels. Due to this, the use of the available national waste biomass supply must be carefully considered, taking into account the emissions reduction pathways of not only domestic aviation, but also harder-to-abate sectors of the economy such as international aviation[vi] and shipping where few other decarbonisation alternatives are realistically available.[51] Also importantly, due to the potential prioritisation of other sectors for waste biomass feedstocks and the large range in emissions abatement associated with SAF (in some cases SAF emissions can exceed fossil fuels), any feedstocks being potentially considered for SAF production (if SAF is deemed a reasonable way forward for domestic aviation) will need to be thoroughly assessed in order to ensure that the sector can achieve its goal of net zero emissions by 2050.[52]

[vi] This is reiterated in the Air Transport Action Group report, Waypoint 2050, where it is stated that 'traditional liquid fuels are expected to remain necessary for long-haul aircraft…., but with a transition towards 100% sustainable and low carbon sources.'

Batteries do not have sufficient specific energy to meet aircraft weight requirements and due to maximum theoretical energy densities, will be unable to decarbonise all of New Zealand's domestic routes at present without very significant reductions in airplane size. As a result, many more flights will be required to transport a similar number of passengers across the domestic network, or the alternative is significantly shorter flight lengths. The largest electric plane currently being designed is a 100-seater model from Wright Electric,[vii] specifying a range of 500 km.[47] After accounting for the legal distance requirements, this range reduces to 184 km, potentially enabling 12.5% of current domestic routes to be electrified. Another innovator focused on battery-electric flight, Heart Aerospace, are attempting to overcome this hurdle by producing planes powered by a combination of batteries and liquid fuels.[48] The plane they are designing, a 30-seat battery-electric hybrid, is expected to have a hybrid range of 600 km by the late 2030's.

This report, from a technical perspective, has identified potential *improve* options to replace jet fuel in New Zealand's domestic aviation sector. However, despite the physics being favourable in some cases, there are still critical technology, infrastructure, economic and regulatory barriers to overcome as these options (and the industries associated with them) are currently pre-commercial on the TRL scale.

Whether green hydrogen, sustainable aviation fuel, or a combination of the two are chosen to decarbonise domestic aviation to ensure Kiwis and our visitors can fly with low emissions around Aotearoa (or an alternative *avoid* or *shift* approach is taken to reduce domestic aviation's emissions), industry and government must work together to enable and accelerate the transition to a future where low emissions, long distance domestic travel in New Zealand is readily available.

[vii] Note that Wright Electric announced that they were developing a 186-seater electric aircraft in 2020, however as of the publication of this report, there is no information in regard to this model on their website.

Appendix A: Ministry of Transport Modelling

Number of flights	**2016**	**2017**	**2018**	**2023**	**2028**	**2033**	**2038**	**2043**
Airbus A320	49699	51585	53984	64750	74945	84981	96645	109809
ATR 72	51267	57112	59383	66500	81916	86789	83380	79861
Dash Q300	71133	60797	55784	35000	8714	0	0	0
Small aircraft	21375	14738	10796	8750	8714	9040	9475	9982
Total	***193474***	***184232***	***179947***	***175000***	***174289***	***180810***	***189500***	***199652***

Fuel usage (kt)	**2016**	**2017**	**2018**	**2023**	**2028**	**2033**	**2038**	**2043**
Airbus A320	158.8	164.8	172.5	206.7	238.3	269.2	305.0	345.2
ATR 72	39.6	43.4	44.9	49.3	59.0	62.3	59.8	57.3
Dash Q300	61.5	52.3	48.0	30.1	7.5	0.0	0.0	0.0
Small aircraft	4.7	4.7	3.5	2.8	2.8	2.9	3.0	3.2
Total	***264.7***	***265.3***	***268.8***	***288.9***	***307.6***	***334.4***	***367.9***	***405.7***

Appendix B: Aircraft Specifications

Aircraft[53]	Dry weight (kg)	Max. take-off weight (kg)	Max. landing weight (kg)	Max. Fuel (m^3)	Total energy efficiency
Airbus A320	42600	78000	66000	27.2	35%
Airbus A321	48500	97000	77800	30.0	35%
ATR 72	13500	22800	22350	6.3	20%
Dash Q300	11791	19500	19050	6.6	20%
Small aircraft	4932	7766	7605	2.5	20%

Aircraft	Cabin diameter (m)	Cabin length (m)	Passenger numbers[viii]
Airbus A320	3.70	27.51	173.3
Airbus A321	3.70	34.44	217[26]
ATR 72	2.57	17.95	68.0
Dash Q300	2.52	12.60	50.1
Small aircraft	1.80	7.67	11.3

[viii] From Ministry of Transport modelling unless specified.

Appendix C: Air New Zealand Routes

Origin	Destination	Distance (km)	Plane (2023 fleet)	Plane (2043 fleet)
Auckland	Bay of Islands	203	Dash Q300	ATR 72
	Blenheim	517	ATR 72	Airbus A320
	Christchurch	758	Airbus A320	Airbus A320*
	Dunedin	1056	Airbus A320	Airbus A320*
	Gisborne	346	Dash Q300	ATR 72
	Invercargill	1183	Airbus A320	Airbus A320*
	Napier	343	ATR 72	Airbus A320
	Nelson	503	ATR 72	Airbus A320
	New Plymouth	245	ATR 72	Airbus A320
	Palmerston North	387	ATR 72	Airbus A320
	Queenstown	1037	Airbus A320	Airbus A320*
	Rotorua	187	Dash Q300	ATR 72
	Taupō	229	Dash Q300	ATR 72
	Tauranga	151	Dash Q300	ATR 72
	Wellington	490	Airbus A320	Airbus A320*
	Whangārei	139	Dash Q300	ATR 72

*These routes are replaced with Airbus A321 aircraft in one of the hydrogen retrofit modelling scenarios.

Origin	Destination	Distance (km)	Plane (2023 fleet)	Plane (2043 fleet)
Wellington	Blenheim	74	Dash Q300	ATR 72
	Christchurch	302	Airbus A320	Airbus A320*
	Dunedin	611	Airbus A320	Airbus A320*
	Gisborne	402	Dash Q300	ATR 72
	Hamilton	398	ATR 72	Airbus A320
	Invercargill	767	Dash Q300	ATR 72
	Napier	274	Dash Q300	ATR 72
	Nelson	128	Dash Q300	ATR 72
	New Plymouth	261	Dash Q300	ATR 72
	Queenstown	645	Airbus A320	Airbus A320*
	Rotorua	378	Dash Q300	ATR 72
	Tauranga	420	Dash Q300	ATR 72
	Timaru	447	Dash Q300	ATR 72
Christchurch	Dunedin	309	ATR 72	Airbus A320
	Hamilton	679	ATR 72	Airbus A320
	Hokitika	166	Dash Q300	ATR 72
	Invercargill	466	ATR 72	Airbus A320
	Napier	576	ATR 72	Airbus A320
	Nelson	255	Dash Q300	ATR 72
	New Plymouth	513	Dash Q300	ATR 72
	Palmerston North	434	ATR 72	Airbus A320
	Queenstown	357	ATR 72	Airbus A320
	Rotorua	675	ATR 72	Airbus A320
	Tauranga	714	ATR 72	Airbus A320

*These routes are replaced with Airbus A321 aircraft in one of the hydrogen retrofit modelling scenarios.

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