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Journal of the Royal Society of New Zealand

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/tnzr20

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To cite this article: Paul Callister & Robert I. McLachlan (2024) Managing Aotearoa New Zealand's greenhouse gas emissions from aviation, Journal of the Royal Society of New Zealand, 54:4, 412-432, DOI: 10.1080/03036758.2023.2212174

To link to this article: https://doi.org/10.1080/03036758.2023.2212174

Published online: 25 May 2023.

JOURNAL OF THE ROYAL SOCIETY OF NEW ZEALAND
2024, VOL. 54, NO. 4, 412–432
https://doi.org/10.1080/03036758.2023.2212174

RESEARCH ARTICLE

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Managing Aotearoa New Zealand's greenhouse gas emissions from aviation

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ABSTRACT

Prior to COVID, the global aviation industry was growing rapidly. Growth has now resumed and is predicted to continue for at least the next three decades. Aotearoa New Zealand has particularly high aviation emissions and has been on a very rapid growth path that is incompatible with the Paris Agreement on climate change. Government, intergovernmental, nongovernmental, academic and industry sources have proposed technological innovations to address aviation emissions. These include sustainable aviation fuels, electric and hydrogen powered aircraft, and increases in efficiency. We review these and assess that none of them will lead to a significant reduction in emissions in the short to medium term. In addition, we demonstrate that even very aggressive uptake of new technology results in the New Zealand aviation sector exceeding its share of the carbon budget as determined by the Paris Agreement. Therefore, we examine the fundamental drivers of growth in aviation: the tourism and airport industries, emissions pricing and substitutes, and the distribution of air travel. Governance of this sector is challenging, but it is changing rapidly. We conclude that a national aviation action plan needs to be developed and implemented based on the 'Avoid/Shift/Improve' framework in use in other areas of transportation planning.

ARTICLE HISTORY
Received 3 October 2022
Accepted 29 April 2023

HANDLING EDITOR
Bruce Glavovic

KEYWORDS
Aviation emissions; sustainable aviation fuel; climate justice

1. Aotearoa New Zealand's commitment within the COP26 'aviation ambition' group

In 2021 New Zealand joined the 'International Aviation Climate Ambition Coalition', committing to 'Preparing up-to-date state action plans detailing ambitious and concrete national action to reduce aviation emissions' (International Aviation Climate Ambition Coalition 2021). In light of this pledge, yet mindful that ICAO is far from the only or even the most important actor in aviation emissions (Rutherford 2021; Laville 2021), we review national and global aviation emissions and examine the various measures that are in place and that have been proposed to address them. What does 'ambitious and

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concrete action' to reduce aviation emissions look like for New Zealand? Many factors–the urgent need to phase out the burning of fossil fuels, New Zealand legislation, the Government's climate goals, international agreements and emerging international action–point in favour of reducing aviation emissions. New Zealand's distinctive situation and the novelty of the challenge indicate that all possible solutions should be examined carefully.

Aviation is not only a large industry and a large emitter. It also underpins tourism and trade, and it links globally dispersed families. New Zealand's geography and infrastructure influence even domestic travel. If a domestic Sustainable Aviation Fuel (SAF) industry were to develop, then agriculture, land use and renewable energy use would be implicated. The rapid rise of cheap and comfortable air travel and its glamorisation in the media has built support for the status quo and made addressing its emissions more difficult politically. Nevertheless, as other jurisdictions begin to refine their options, New Zealand is in a good place to start working out the most suitable way to address aviation emissions. The Climate Change Commission has been asked to advise by 2024 on whether international aviation and shipping should be included in the target of net zero long-lived greenhouse gases by and beyond 2050.

In this paper, we assess the status quo and current proposals from key national and international government, nongovernmental, intergovernmental, industry and academic sources (see Table 1); as we shall see, future pathways are diverse and uncertain. We will interpret these under the 'Avoid/Shift/Improve' framework, which was introduced in the context of urban transport in the early 1990s and which has since spread to all areas of environmental management (Akenji et al. 2021; Roy et al. 2021). (*Avoid* trips, *shift* trips to lower-impact modes and *improve* the remaining high-impact trips.) On the whole, industry and some governmental proposal favour 'improve' strategies, with continued growth of aviation and rapid expansion of new technologies, while environmental NGOs emphasise the role for 'avoid' and 'shift'.

We begin by describing New Zealand's aviation current emissions and governance in Section 2. Section 3 covers the primary options to improve air travel: improvements to existing technology; zero-tailpipe-emission aircraft; sustainable aviation fuel; and

Table 1. A typology of organisations and sources relevant to aviation emissions and leading instances drawn on in this study.

Industry	International Air Transport Association
	Air New Zealand
	British Petroleum
	Airports New Zealand
	New Zealand Tourism Industry Association
Governmental	New Zealand Ministries of Transport and Environment
	New Zealand Parliamentary Commissioner for the Environment
	European Union *Fit for 55* and *ReFuelEU*
	United Kingdom *Jet Zero*
Nongovernmental	International Council on Clean Transportation
	Transport and Environment
	Aviation Environment Federation
	International Council for Sustainable Aviation
	Science Based Targets Initiative
Intergovernmental	Intergovernmental Panel on Climate Change
	International Civil Aviation Organisation
	International Energy Association
Academic	Climate change: mitigation, governance, justice
	Studies of aviation, aerospace, and tourism industries

offsetting. We find that pathways demanding a significant contribution from zero-tail-pipe-emission aircraft are implausible on grounds of lack of technological readiness and extreme energy requirements. Nevertheless, such scenarios enjoy a sustained media and corporate presence, raising the prospect that they are functioning as 'technologies of prevarication'. Similar arguments apply to sustainable aviation fuel, which in industry scenarios is expected to provide the bulk of emissions reductions. Although we do not rule out some contribution, we are pessimistic that the very large quantities of fuel required can be supplied sustainably. In Section 4, we consider the total future carbon emissions from New Zealand aviation. We demonstrate via a simple model that the requirements of finite carbon budgets implied by the Paris Agreement on Climate Change mean that even very aggressive technological progress and uptake are not enough to meet New Zealand's climate target of contributing to the global target of limiting warming to 1.5°C. Therefore, in Section 5, we turn to broader issues of governance, equity and the underlying drivers of aviation growth. We conclude in Section 6 by reviewing how New Zealand could approach the development of its state action plan on aviation emissions. Through its membership of the Ambition Coalition, New Zealand has already had some impact: in September 2022 ICAO agreed to an aspirational goal of net zero aviation by 2050 (ICAO 2022), to be delivered through voluntary actions by the states. The governance process and the balancing of interests are key factors that will influence New Zealand's plan.

2. New Zealand's aviation emissions

New Zealand's aviation emissions rose 116% from 1990 to 2019 to reach 4.9 Mt CO_2, with international emissions tripling (see Figure 1). Aviation rose from 8% to 12% of gross CO_2, much higher than the equivalent global proportion, which rose from 2.3% to 2.8%. Non-CO_2 effects are uncertain, but are estimated at twice the CO_2 effects (European Commission 2021; Klöwer et al. 2021). New Zealand ranks 6th in the world for per-capita aviation emissions, at 1 tonne CO_2, about 10 times the world average. It ranks 4th for per-capita domestic aviation emissions (more than Canada, a much larger country) and 6th for international aviation emissions (Global Sustainable Tourism Dashboard 2021).

Two key factors behind this growth are price and quality. Since Air New Zealand launched their Auckland–London flight in August 1982, prices have fallen 70% in real terms, while incomes have risen, so that prices relative to income have fallen by a factor of 6. In addition, long-haul flights have become steadily more reliable and comfortable over the decades. More passengers mean more flights. The Tourism Satellite Account (Statistics New Zealand 2019) lists more than 100 new and expanded routes during the 2015–2019 period of very rapid growth, some of them extremely long, such as Auckland to Buenos Aires, Chengdu, Chicago, Doha, Dubai and Ho Chi Minh City.

In addition, international travel is closely linked to the rise of globally dispersed families. For New Zealanders returning from overseas, 15% had been travelling for business or education, 42% for holidays, and 36% to visit friends and family. (These travellers could be resident either in New Zealand or overseas.) Of non-New Zealand travellers, 12% were travelling for business or education, 52% for holidays, and 28% to visit friends and family (Statistics New Zealand 2019). The proportion of the New Zealand population born overseas was 17.5% in 1996 and has risen steadily, reaching

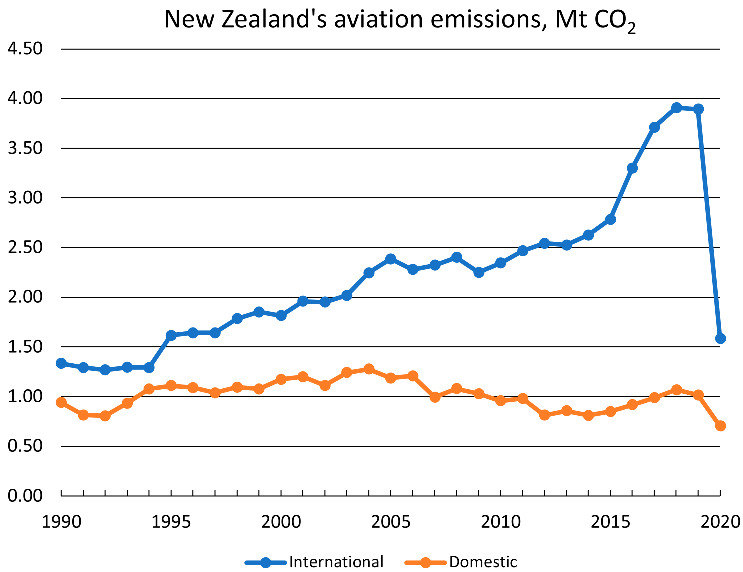

Figure 1. New Zealand aviation CO_2 emissions, 1990–2020 (UNFCCC 2021). Note the rapid rise in emissions over the 4-year period 2015–2019, +40% for international and +20% for domestic emissions.

27.4% in 2018. The two largest groups of migrants are from the UK (265,000 people) and China (144,000). Perhaps 1 million New Zealanders live overseas, including one in six Māori (Rae and Callister 2019).

Emissions from domestic aviation are included in the New Zealand Emissions Trading Scheme (ETS). There is no fuel excise tax. There are some fees, such as a $1.60 per passenger CAA fee. At an ETS price of $77/t$CO_2$, a return flight from Auckland to Christchurch (0.194 tCO_2) the ETS charge is $14.90, out of a ticket price which can range from $118 to $920. Some airlines also offer optional carbon offsetting schemes, such as Air New Zealand at $24/t$CO_2$ or $4.68 for Auckland–Christchurch return. Emissions from international aviation are not included in the ETS. GST is not charged on international flights, or on domestic flights which connect to international flights. There is an airport and security fee of $50 per ticket. (All dollars are nominal New Zealand dollars unless otherwise stated.)

3. Pathways towards reduced aviation emissions: global and technological perspectives

3.1. Existing high-level scenarios

In this section, we describe a range of recent scenarios from around the world that indicate how aviation emissions might be reduced in coming decades. We will see that they vary greatly in their traffic levels and in the relative contributions of different mitigation factors. Governance mechanisms that could realise the scenarios have not yet been given much attention, with the European Union's plan being an exception. The scenarios are summarised in Table 3.

The International Air Transport Association, a trade association of the world's airlines, initially established a goal of halving net emissions between 2010 and 2050. In

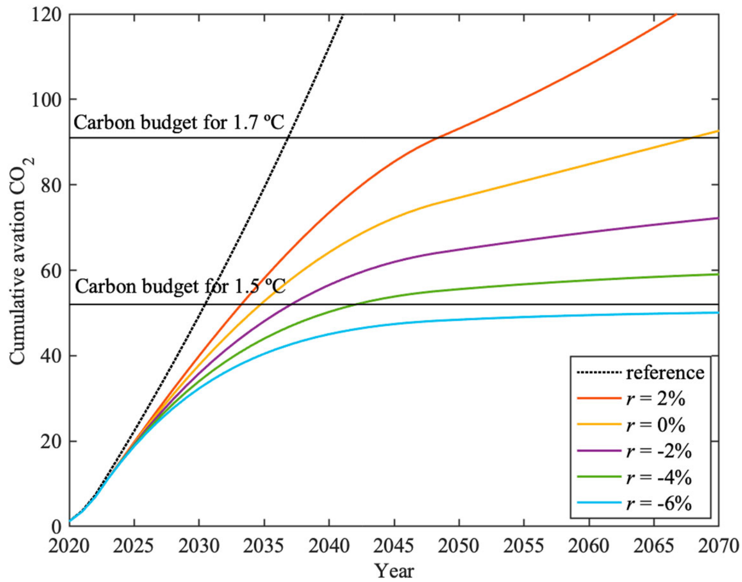

Figure 2. Model pathways for future cumulative CO_2 emissions from New Zealand aviation under different growth rates *r*, with traffic returning to 2019 levels in 2023 and 20% efficiency gains and 100% SAF by 2050. The horizontal lines show the carbon budgets under two global temperature targets. The reference case refers to 2% annual growth using existing technology and fuel.

2021, this was strengthened to net zero by 2050. The IATA plan forecasts passenger numbers to grow from 4.5 billion in 2019 to 10 billion in 2050, with net zero emissions to be achieved by 65% SAF, 13% new technology such as hydrogen aircraft, 3% operations, 11% carbon capture and storage (CCS), and 8% offsetting. SAF use in the aviation industry would grow from 0.2 Mt in 2019 to 18 Mt in 2030 and 180 Mt in 2040, while it is claimed that the industry is not reliant on zero-tailpipe-emission aircraft to meet net-zero (Walsh 2021). The actual resolution agreed by members, however, is considerably less specific (IATA 2021). It does not contain these targets or mechanisms by which they would be met; the agreement covers general aspirations and calls for government support. In particular, governments are asked that their aviation plans do not rely on ticket or carbon taxes.

The International Energy Agency released an influential net zero study in 2021 (IEA 2021). For aviation, their scenario involves business travel and flights longer than 6 hours held at 2019 levels; regional flights shifted to high-speed rail where feasible; air travel to

Table 2. Key aspects of New Zealand's aviation emissions.

• CO_2 4.9 million tonnes in 2019
• Per-capita 6th highest globally at 1 tonne CO_2 (cf. US 0.56t, EU 0.65t)
• 12% of CO_2 emissions
• Proven ability to grow emissions rapidly: International +40%, domestic +20% in 2015–2019
• International passengers fell 97.6% in the 12 months to March 2021
• Domestic aviation CO_2 included in NZ ETS and the falling cap on net emissions
• Founding member of the International Aviation Climate Ambition Coalition, committed to presenting an 'ambitious and concrete national action plan' in 2022 to reduce aviation emissions

Table 3. The proposals and estimates discussed in the text. The UK CCC data is their 'Balanced Net Zero' pathway. The ICCT estimate is based on the potential maximum technology and feedstock supply. The sustainable aviation fuel (SAF) proportions do not take into account the lifecycle emissions of the fuels (e.g. land use, processing, infrastructure, renewable energy).

Scope	Study	Proposed SAF proportion	Traffic growth by 2050
EU	Fit for 55	20% by 2035, 63% by 2050	
EU	ICCT	20% by 2035	
UK	Jet Zero	14% by 2050	54%
UK	CCC	25% by 2050	25%
UK	Absolute Zero		−100%
world	IEA SDS	50%	180%
world	IEA Net Zero	78%	14%
world	BP Net Zero	60% by 2050	80%
world	IATA	65% by 2050	120%
world	SBTi		142%
New Zealand	Air NZ	86% by 2050	75%

increase 14% between 2019 and 2050; advanced biofuel and e-fuel use to reach 50% by 2040 and 78% by 2050; and carbon prices across all advanced economies rise to US $130 by 2030 and US$250 by 2050. They assign zero-tailpipe-emission aircraft 2% of air travel in 2050.

A third global study comes from BP. The *BP Energy Outlook* for 2019 (BP Energy Outlook 2019) sees total oil demand continuing to increase past 2040, with 64% of the increase coming from aviation. In 2020, the *Outlook* introduced two new scenarios (BP Energy Outlook 2020), 'Rapid' and 'Net Zero', along with BAU. They involve aviation nearly doubling by 2050, accompanied by 35% efficiency improvements and either 30% or 60% share of biofuels, along with a carbon price of NZ$250 by 2035 and NZ$380 by 2050 in developed countries.

Two principal jurisdictions that have begun efforts to address aviation emissions are the EU and the UK. This work is not new, as intra-EU aviation has been partly covered by the EU ETS since its inception. The EU was sceptical of the CORSIA scheme and had always intended to review its performance and their regulation of extra-EU aviation. But the EU's new NDC under the Paris Agreement, to cut emissions to 55% below 1990 levels by 2030, via the 'Fit for 55' program, has hastened this work. Under 'Fit for 55', the EU will phase out free ETS allowances for intra-EU aviation (currently covering about half of such travel) over 2024–2027, and reduce the emissions cap of the whole ETS faster. They will tax jet fuel for intra-EU flights from 2023, with the tax rising linearly to € 0.38/L (equivalent to € 154/tCO_2) by 2033. For all flights, an SAF mandate would rise from 5% in 2030 to 20% in 2035 and 63% by 2050, for which only waste wood and fats and e-fuels would qualify. Taxation of extra-EU flights would be left up to each country to determine, while CORSIA would remain in place. Their model forecasts a baseline growth in traffic of 20% over 2015–2050, with the new proposals reducing emissions by 60% for an overall reduction of 52%. The NGO *Transport and Environment* said the EU should reject CORSIA, apply the ETS to all flights, apply a multiplier for non-CO_2 effects, and dedicate ETS revenues to e-fuel production (Dardenne 2021).

Meanwhile, the UK has included international aviation in its 6th carbon budget for 2033–2037, leading to their 'Jet Zero' plan. The UK's *Jet Zero* has a headline goal of net zero aviation by 2050. It sees aviation emissions falling 42% from 2019, and allows traffic growth of 54%. Reductions are to be comprised of demand reductions 8.8%; efficiency gains 36%; zero emission aircraft 4.1%; SAF 14.4% and offsets 36.7%. SAF proposals are oriented around the establishment of a very large domestic industry, with 25–125 large SAF plants in the UK by 2050. Other components are to retain the ETS for UK–EU flights, to 'strengthen carbon pricing', and to require zero emission domestic aviation by 2040. *Jet Zero* was poorly received by environmental groups, who found it inconsistent with the Paris Agreement (Rutherford 2021) and too optimistic about new technologies while lacking clear price signals and regulation of airports and frequent flyer programmes (Aviation Environment Federation 2021). Further, it assumes that the government will have plentiful carbon removal options in place for 2050, which should be the industry's job (Finch 2021).

In another scenario for the UK, the UK Committee for Climate Change's 'Balanced Net Zero' pathway foresees passenger growth of 25% by 2050 and no increased airport capacity. Efficiency improvements and a 25% SAF share see emissions fall 40% by 2050. The UK CCC finds that demand could be managed by 'carbon pricing, a frequent flyer levy, fuel duty, VAT or reforms to Air Passenger Duty, and/or restricting the availability of flights through management of airport capacity' and is confident, based on discussions at the Climate Assembly, that this would be acceptable to the public. This pathway, and its embedded growth, has been criticised on the grounds that it privileges the aviation sector at the expense of all other sectors (Somerville 2021).

We now turn to New Zealand. Air New Zealand's 2021 sustainability report (Air New Zealand Sustainability Report 2021) was their first to outline a schematic pathway to reach net zero by 2050. It involves 75% passenger growth by 2050, with net zero to be achieved by 20% of the emissions cuts coming from new conventional aircraft; 20% from zero-tailpipe-emission aircraft; 50% from SAF (implying an 86% SAF mandate); 2% from operations and 8% from offsetting. They see a need for strong government action to establish a domestic SAF industry, first based on forestry residues with a domestic plant running by 2027, then on waste, and then (from 2045) on whole logs and e-fuels, with steady progress ensured via an SAF mandate (Air New Zealand Sustainable Aviation Fuel White Paper 2021).

The Ministry of Business, Innovation, and Employment will advise on an aviation SAF mandate in 2023, with the mandate proposed to start in 2025. The Climate Change Commission will advise in 2024 on whether New Zealand's 2050 emissions target should be amended to include emissions from international shipping and aviation and if so, how. Legal advice is that these should also be included in NDCs (Dejon 2021).

3.2. Zero-tailpipe-emission aircraft

There is broad agreement that improvements in fuel efficiency will continue, although the wide range of values attributed to efficiency in the scenarios above suggest that the 2% per year improvement targeted by ICAO (2022) is ambitious. The IPCC 6th assessment found that 'the literature does not support the idea that there are large improvements to be made in the energy efficiency of aviation that keep pace with the projected growth in air transport' (IPCC 2022). But most attention has been focused on projects and proposals for zero-tailpipe-emission aircraft, of which the three main contenders are battery electric, hydrogen electric and hydrogen combustion. Numerous small electric aircraft under development, some aiming at commercial use in the mid-2020s, and Airbus are aiming for hydrogen-powered flight by 2035.

As no such commercial aircraft exist at present, the uncertainties are large. The engineering challenges for usable performance even from small electric aircraft are substantial; the short-hop 19-seater that Sounds Air had hoped to operate in New Zealand by 2026 was cancelled in September 2022 (Callister and McLachlan 2021) and replaced by a 30-seat hybrid, whose engineering details have not yet been released. Zero-tailpipe-emission aircraft do not enjoy the energy efficiency gains of electric or hydrogen land transport, because the batteries or tanks have to be lifted. A schematic hydrogen aircraft (Mukhopadhaya and Rutherford 2022) is less energy efficient than a standard aircraft.

If these aircraft do become a reality, they would need to be supplied with electricity or hydrogen. Mason et al. (2017) find that under business-as-usual growth in aviation, 42 TWh of electricity would be needed by 2050–equal to New Zealand's entire current supply. In addition, New Zealand would be attempting to replace all the fossil fuels used in land transport, and a lot of those used in industry, with electricity and/or hydrogen at the same time. Electrolysers tend to be placed where the fuel is needed, indicating a need for a 3800 MW electrolyser at Auckland airport, six times the power of the Manapouri power station. Power could be provided, for example, by 14,000 MW of wind turbines, i.e. 63 copies of the Turitea wind farm that is currently under construction at a cost of $370 million. The resulting substantial increase in intermittent supply in the electricity grid would mean that more storage or oversized electrolysers would also be needed. In other words, the energy requirements are extreme.

3.3. Sustainable aviation fuels

The lion's share of many aviation pathways focus on sustainable aviation fuels (SAF) (Rae and Callister 2019). The challenges of these pathways are extreme. In 2019, 0.05% of global aviation fuel was biofuel, made from food crops and derivatives such as tallow and used cooking oil. These are in limited supply and have dangerous side effects, including impacts on human and animal food supply and prices, and product substitution (e.g. palm oil substituting for other vegetable oils). They are the cheapest biofuels available at present, with prices on neste.com typically about 50% higher than kerosene; both fossil and bio-jet fuel prices are highly volatile, both varying by a factor of 5 since the start of 2020. Future prices will depend on international trends in mandates and subsidies, as feedstock supply is limited.

Therefore, pathways with high levels of SAF look to other feedstocks, especially wood. One plant, producing bio-oil from sawdust in Gävle, Sweden, is in commercial operation. A report from the ICCT (O'Malley et al. 2021) concluded that the EU could be capable of producing 2 Mt a year of wood-based biofuel by 2035, about a quarter of the proposed mandate in 'Fit for 55' and slightly more than New Zealand's 2019 consumption of jet fuel. Closing the apparent gap–a factor of 100–will need close attention. An initial study for New Zealand estimates that a $520 million plant could produce 57 million litres of fuel from wood per year, 0.7% of New Zealand's liquid fuel consumption (Bio-Pacific Partners 2021).

E-fuels, made directly from water and carbon dioxide (sourced from the air, from flue gases, or from plants) and renewable electricity, can potentially be supplied in any amount. They also eliminate some of the environmental effects of biofuels and some of the non-CO_2 effects of burning fossil fuels in aircraft. A number of small trial plants are under construction in Europe. The obstacles are cost and (if the industry were to scale up) renewable electricity supply. The ICCT estimate (O'Malley et al. 2021) that at \$1300/tCO_2 support–five times the cost of jet fuel–the EU could produce 0.23 Mt a year of e-fuels by 2035, one-tenth of the proposed mandate under 'Fit for 55'. The energy requirements are about twice that of hydrogen electrolysis.

An ambitious scenario for 2035 for aviation SAF for New Zealand would involve two \$520 million wood-based biofuel plants (producing 57 million litres a year each) and one 100 MW e-fuel plant producing 40 million litres a year. Together they would provide 8% of New Zealand's aviation fuel at 2019 levels of demand. It should be considered whether this could be achieved simultaneously with a rapid expansion of green hydrogen and low-carbon biofuel for non-aviation applications. In addition, if demand was to grow as envisaged by existing airport expansion plans, total emissions would grow while the difficulty and cost of meeting such a proportion of SAF would increase.

Overall, although New Zealand has reasonable potential resources of both renewable electricity and of feedstock for advanced biofuels, significant capital investment and advance planning would be required to exploit them. Nevertheless, sustainable aviation fuel mandates open up synergistic pathways in which the higher costs of sustainable fuels lead to greater focus on efficiency and lower traffic growth.

3.4. Offsetting

Prior to 2020, the main climate strategy put forward by the aviation industry was offsetting. This formed the basis of ICAO's CORSIA scheme, originally intended to cap net emissions at 2020 levels. When COVID led to a fall in traffic in 2020, the baseline was reset to 2019 levels for 2021–2023 and 85% of 2019 levels thereafter. A study for the European Commission found that none of the offsetting programmes approved under CORSIA met all of the quality requirements; that all of them had issues with double counting–for example, claiming credit for emission reductions already covered by national climate targets; that the price of offsets (less than € 1) provides no incentive to reduce emissions and that secrecy at ICAO prevents independent verification of the scheme's operation (Dardenne 2021).

The entire topic of offsetting and its role in climate solutions is controversial. As Carton et al. (2021) remark,

> [B]urning fossil fuels moves carbon from permanent storage into the active carbon cycle, causing an aggregate increase in land, ocean, and atmospheric carbon. Once added, this additional carbon cannot be removed through natural sinks on time-scales relevant to climate mitigation.

The issue is particularly acute for New Zealand, where mitigation pathways require forestry to rapidly and continuously increase to 2050 and beyond. Emissions from the first half of the century would be stored above ground and maintained by our descendants in the second half of the century. In addition, current proposals are for twothirds of New Zealand's Paris Agreement target for 2030 to be achieved internationally–much of which could again be by offsets. In other words, the availability of offsets has in part determined a pathway which involves higher fossil fuel use than would otherwise be the case. Therefore, the renewed emphasis since 2020 on true net zero pathways for aviation that involve only small amounts of offsetting is welcome.

3.5. Limits of technological innovation

The obstacles in the way of a technological solution to aviation emissions–that is, an approach purely based on 'Improve'–are formidable. In addition to cost, technological readiness, feedstock supply and environmental side effects, there are difficult timing issues. On one hand, emission reductions are needed now, but the alternatives are not ready, while on the other, it is hard to reliably forecast the future cost of different solutions to make the necessary decisions now. All of this is seemingly at odds with the reliance of institutional pathways on technological solutions. A comprehensive study by Grewe et al. (2021) considered a wide range of scenarios for growth, technology and COVID response, finding that only the most optimistic scenarios involving rapid uptake of new technology could stabilise aviation's climate impact in the second half of the century, but that a technology assessment expert group found these scenarios implausible. The wide range of traffic growth in the studies cited indicates there is no consensus on the way forward. Some studies do include high carbon charges with broad coverage, which would have some impact on the 'Avoid' and 'Shift' factors for aviation, moderating demand for long-haul flights in particular and shifting some of them to nearer destinations where other travel modes are an option.

New technology plays a complex role in climate change with, by now, a long history. McLaren and Markusson (2020) discuss 'technologies of prevarication', outlining a cycle in which technological promises 'raise expectations of more effective policy options becoming available in the future, in turn justifying existing limited and gradualist policy choices and thus diminishing the perceived urgency of deploying costly and unpopular, but better understood and tested, options for policy in the short term '. Examples include forestry, nuclear power, energy efficiency, (bioenergy) CCS, direct air capture of CO_2 and solar radiation management. Peeters et al. (2016) study this specifically for aviation, identifying 'technology myths' (proposed solutions that are either abandoned, unrealistic, over-optimistic or at too early a stage to reliably assess) with the consequence that 'politicians may embrace myths to justify non-action'.

4. Carbon budgets: what is a fair share for aviation emissions?

We now turn to the other determinant of aviation emissions (along with efficiency): traffic volumes. A common approach is to assume that traffic growth will continue in an almost unrestrained fashion, based on past behaviour and on the principle identified by Schafer and Victor (2000) that widely diverse groups of people spend a constant proportion of their time and of their income on travel. Rising incomes therefore lead to more expensive, faster travel modes, i.e. to more flying. For example, the IEA's *Sustainable Development Scenario* involves growth of 3.4% per year out to 2070, or 180% growth over 2019–2050 (IEA 2020). The Science Based Targets Initiative guidance for aviation under 2°C is based on a similar model, 2.9%/yr growth (142% over 2019–2050) and a 63% decline in emissions intensity, leading to a 10% reduction in emissions overall (Science Based Targets 2021). (In contrast, the he IEA Net Zero scenario curtails some flying to yield 14% traffic growth by 2050 and an 80% reduction in emissions overall (IEA 2021).)

However, the targets of the Paris Agreement imply that there is a fixed global budget for greenhouse gas emissions, traditionally distributed between the main greenhouse gases to give a global carbon budget for any given temperature rise. This raises questions about how the budget could or should be allocated among different countries and sectors. Here we explore the implications of the approach to carbon budgets (supported, e.g. by the International Coalition for Sustainable Aviation in their submission to the 41st ICAO Assembly (International Coalition for Sustainable Aviation 2022)) in which aviation does not increase its share of CO_2 emissions and, furthermore, we devolve the same requirement to the states. (For high emitters like New Zealand, this is a generous allocation, and would probably not meet the requirements of 'highest ambition' and 'differentiated responsibilities' of the Paris Agreement.)

Our model is constructed as follows. Taking the remaining global carbon budgets for 1.5°C (resp. 1.7°C), and allocating aviation 2.4% of global CO_2, leaves a global carbon budget of 9600 (resp. 16800) $MtCO_2$ (International Coalition for Sustainable Aviation 2022). In 2019, New Zealand was responsible for 0.54% of global aviation emissions. Retaining this share leaves a carbon budget of 52 (resp. 91) $MtCO_2$ for New Zealand aviation. We consider a simple model of traffic volumes in which traffic is 75% below 2019 levels in 2020; 50% below in 2021, 25% below in 2022, and returns to a factor c of 2019 levels in 2023, followed by annual compound growth of rate r. Efficiency improvements reduce fuel demand 20% by 2050, and are thereafter held steady; SAF with a lifecycle emissions reduction of 80% reaches a proportion s by 2050 and is thereafter held steady. Both of these effects are phased in linearly. The results of the model are that with $c = 1$ and $s = 1$ (i.e. 100% SAF by 2050), only very aggressive traffic reductions of 6% per year keep cumulative emissions under the 1.5°C budget. Other scenarios see the budget (see Figure 2) exhausted in the 2030s. Scenarios that meet the 1.5 and 1.7°C carbon budgets are presented in Table 4.

To put this another way, in light of New Zealand's commitment to 1.5°C, without radical efficiency measures there are just 10 years of flying left at 2019 levels. Furthermore, there is no clear justification for a 2019 baseline, which would act to grandfather in the very rapid increases of the late 2010s. The Paris Agreement acknowledges the principles of fairness, responsibility, and capability, and calls for the highest ambition. Adopting a 1990 baseline would reduce New Zealand's aviation carbon budget by a quarter. Under the carbon budget approach, very sharp reductions in emissions are needed, leaving no other option than to focus on the 'Avoid' and 'Shift' segments. However, earlier action–especially in the 2020s–makes meeting the budgets easier. Ensuring that New Zealand's 2019 levels are never regained would make meeting future carbon budgets significantly easier.

The 2019 study *Absolute Zero* from the UK FIRES consortium (Allwood et al. 2019) argues that radically new technologies–like zero-tailpipe-emission aircraft or sustainable aviation fuel–will not be able to scale up to make a difference within 30 years. Therefore, virtually all sources of emissions have to be phased out using today's

Table 4. Six scenarios for New Zealand aviation, combining different traffic growth rates *r*, SAF proportion in 2050 *s*, and cap on traffic in 2023 *c*, that meet the IPCC carbon budget for 1.5°C resp. 1.7°C (i.e. 'well below 2°C').

Traffic growth *r* (from 2023)	SAF by 2050 *s*	Traffic cap *c* (cf. 2019)	Carbon budget	2050 traffic (cf. 2019)
−5.7%	100%	100%	1.5°C	−81%
−8.2%	50%	100%	1.5°C	−91%
−3.2%	100%	75%	1.5°C	−70%
−1.2%	100%	100%	1.7°C	−29%
−3.6%	50%	100%	1.7°C	−64%
+0.1%	100%	75%	1.7°C	−23%

technologies. In the Absolute Zero pathway, conventional aviation is phased out by 2050, while electric flight and e-fuels may allow flight to resume when sufficient zero carbon electricity is available.

Degrowth perspectives reject current aviation industry policy, not just because of its incorporation of unlimited growth but because its reliance on expensive and uncertain future technology aligns it with eco-modernism. Rather than favouring any specific 'solution' (e.g. 'polluter pays'), degrowth seeks to avoid trading off social, environmental, and economic impacts, and asks that the ultimate purpose and scale of aviation, as an ethical and political question, should be examined by society as a whole (Köves and Bajmócy 2022).

While these questions remain live, and have scarcely moved into the public arena, it is clear that unrestrained growth of traffic combined with the uncertainties of emission reduction technologies creates risk. We therefore consider in the next section the main drivers of aviation traffic and its growth.

5. The drivers of aviation growth

In this section, we consider factors that affect the growth of aviation, both positively (the airport industry, the tourism industry, and the unequal distribution of flying) and negatively (emission pricing and the availability of substitutes). If technology does not or cannot deliver in time (the 'Improve' factor), then we must rely on 'Avoid' and 'Shift'. The IPCC 6th Assessment concluded that 'The indicative potential of demand-side strategies across all sectors to reduce emissions is 40–70% by 2050 (high confidence)…The greatest *Avoid* potential comes from reducing long-haul aviation and providing short-distance low-carbon urban infrastructures' IPCC (2022).

5.1. Airports

Aviation growth and airport expansion go hand-in-hand. Just as many airlines are state-owned, so are many airports. In 2018, US$737 billion of airport construction projects were in progress worldwide, of which 7% were privately funded. In New Zealand, Auckland Airport's long-held plans for a second runway have been put on hold by COVID, but a $3.9 billion airport redevelopment will go ahead. Wellington Airport is planning to double passenger numbers by 2040. Christchurch Airport is proposing to build an entirely new international airport in Tarras, Otago, to serve the Queenstown–Wanaka region, again prompting environmental concerns. All three airports are partly publicly owned.

The paucity of government regulation or planning for aviation growth, particularly international aviation, or any guidance for the responsibilities of airports, is likely to become the subject of attention in these and in future development plans and in any possible court actions. Citizens and environmental groups can become directly involved in decision making related to airport construction. In the UK, the Balanced Net Zero pathway of the UK CCC requires no net airport expansion in the UK; but eight airports are currently planning expansions.

New Zealand's current aviation emissions plan, prepared in 2016 as an ICAO requirement (Ministry of Transport 2016), takes a 'predict and provide' approach to growth and does not link airport capacity to emissions growth. It is now out of date, predicting international emissions in 2019 of 2.3–2.7 $MtCO_2$, one-third less than the actual emissions of 3.9 $MtCO_2$. In 2021 NZ Airports supported this plan in their submission to the Climate Change Commission, and wrote that New Zealand airports have almost no contribution to aviation greenhouse gas emissions; the amount of flying was not mentioned as a factor in emissions (NZ Airports Association 2021). The future pathway selected or followed by New Zealand will both depend on, and directly influence, our future airport capacity; so the planning process for the airport industry must become part of any overall plan for the sector.

5.2. Tourism

The growth of aviation has been tightly linked to the growth of tourism, both in New Zealand and worldwide. Through the 2010s the marketing of tourism continued to evolve, with talk of adventure and bucket lists for the upper middle classes in developed countries, and privilege and luxury for those on the highest incomes.

According to Higham et al. (2022), until national tourism administrations 'are required to develop metrics of success aligned with the Sustainable Development Goals and the Paris Agreement, any change will only happen as a result of other government departments that have a sustainability remit, particularly from those in charge of transport, energy and climate.' Indeed, New Zealand's state tourism body has been slow to address emissions. The 2019 Government Tourism Strategy was focussed on 'sustainable tourism growth', but did not mention aviation emissions at all. A 2019 industry strategy ('now with sustainability firmly at its heart') briefly mentioned aviation emissions in the context of the threat that tourists might become environmentally responsible and not want to fly as far as New Zealand (Tourism Industry Association 2019). More attention was paid by the Parliamentary Commissioner for the Environment, who in 2021 made tourism aviation emissions one of four key focus areas (Parliamentary Commissioner for the Environment 2021).

Internationally, the response has been no better. The WTTC, the peak global body for the travel and tourism industry, does have a net zero roadmap (WTTC Net Zero Roadmap 2021): it assumes 83% traffic growth from 2019 to 2050, and views the levers for aviation to be new technology, operational efficiency, and SAF–that is, not pricing or demand reduction. They remark that 'especially in aviation, government support is key to realising the potential of the key levers '. At COP26 the 'Glasgow

Declaration on Climate Action in Tourism' was launched; signatories (travel and tourism companies) committed to preparing a plan within 12 months to halve emissions in 10 years and reach net zero by 2050; an analysis by Scott and Gössling (2022) concludes that the declaration is vague and shows a 'worrying unfamiliarity of the strategies by which Paris Agreement compatible energy-emission futures could be achieved and the potential implications for the tourism sector '. Like the airport industry, the tourism industry (presently in a COVID recovery mode) strongly influences future traffic patterns, resulting in the need for a difficult negotiation between the industry, government, and the public; this has started (Parliamentary Commissioner for the Environment 2021) and is sure to intensify.

5.3. Substitutes

The natural experiment of COVID illustrated the availability of substitutes for flying, including flying less, video conferencing (which, although not an exact substitute, has perhaps connected more people than flying ever did), substituting domestic for international tourism and substituting local tourism for distant domestic tourism (Reichenberger and Yeoman 2022). Here we look at land transport as a substitute for domestic air travel. The land transport options are private vehicles or public transport, bus and train. New Zealand's response is hampered by its extreme reliance on private cars–having heavily invested in infrastructure, with large scheduled future investments and one of the highest car ownership rates in the world–and relative underinvestment in regional public transport (Hasan et al. 2019). The passenger rail network is very limited, while a private coach network still exists, but suffers from infrequent service, poor quality, substandard terminals, lack of connectivity and lack of integrated ticketing (Callister and O'Callahan 2021).

Low-occupancy private cars are at present even higher-emission than flying and, despite some regulatory progress, likely to improve only slowly on a fleet-wide basis. This option is high-emission for the vast majority of car owners, and not available at all for people who do not own a car or drive, including many children, elderly and some people with disabilities.

If, in the UK, the rich take trains and the poor take buses (Banister 2018), we suspect that in New Zealand the rich fly or drive and the poor take the bus or do not travel at all. Callister and Galtry (2017) and Callister and O'Callahan (2021) make the case for the positive impact that a high-quality regional bus network would have on social and health inequalities, as well as on greenhouse gas emissions. Unfortunately, there is essentially no ongoing academic research, institutional monitoring or coordinated planning of regional public transport in New Zealand. Until the entire inter-regional transport system is considered as a whole, it will not be possible to assess the case for specific interventions such as rail electrification, resurrection of regional passenger rail or an upgrade to higher-speed trains.

5.4. Emission pricing

Although domestic aviation is included in the ETS, it is unlikely to reduce emissions sufficiently by itself. The behaviour change and technological transitions are too demanding in the required time frame, and prices are unlikely to be allowed to rise high enough. Complementary policies can deliver emissions reductions in a fairer and more orderly way, even under a cap on emissions (Hall and McLachlan 2022). Emerging plans for aviation adopt this view. For example, the EU is proposing to use both an SAF mandate and a fuel tax, in addition to a strengthened ETS and a cap on emissions. European support for rail is also linked to reducing intra-EU aviation. The IEA's net zero pathway also involves significant carbon pricing along with SAF and traffic regulation.

In this context, the preferential tax situation that international aviation enjoys at present is an extremely significant obstacle to emissions reduction. The legal and jurisdictional obstacles to revising it are well known, suggesting an initial focus on other mechanisms such as air passenger duty (Parliamentary Commissioner for the Environment 2021). But now that the EU is proposing to impose an excise tax on jet fuel, the options politically open to other countries may increase (Dardenne 2021).

5.5. The distribution of air travel

The need for a just transition is well established in New Zealand (Huggard 2019). However, a just transition–often seen as focusing on the impacts on workers in fossil fuel industries and on poor people–is but one part of climate justice as a whole. We argue here that climate justice requires examining also the role of rich people, who tend to have high emissions as well as the means to address them.

Personal greenhouse gas emissions are highly unequal and are strongly related to income. Ivanova and Wood (2020) found that the lowest-emitting half of EU households emit an average of 5 tonnes CO_2 e per person; the middle 40%, 10 tonnes; the top 10%, 23 tonnes; and the top 1%, 55 tonnes. For air travel, the effect is even more extreme: 90% of EU households have air travel emissions averaging 0.1 tonnes per person; 9% average 0.8 tonnes; and the last 1% average 22.6 tonnes; its high income elasticity confirms air travel as a 'highly carbon-intensive luxury'. The same is true globally: Gössling and Humpe (2020) find that in any given year 1% of the world's population are extremely frequent flyers, emitting 10 tonnes CO_2 each on average and causing half of all aviation emissions; another 10% fly less and emit 1 tonne CO_2 and the remaining 89% do not fly at all. Other things being equal, an increase in inequality will be associated with an increase in flying, and in increase in GDP will be associated with a disproportionate increase in flying (Schafer and Victor 2000).

This unequal distribution is reinforced by social factors. High socio-economic status people often lead hypermobile lives associated with work and multiple home ownership, and influence the climate crisis through their role as investors, managers, role models and lobbying (Nielsen et al. 2021). Cohen et al. (2018) describe how travel is 'glamorised by a range of social mechanisms, such as visualisations on social media that encourage mobility competition, frequent flyer programme status levels and the mass media and travel industry who depict tourism and business travel as desirable.'

Factors other than income are also relevant to transport equity: race and ethnicity, bodily ability, civic status and age (Gebresselassie and Sanchez 2019). For New Zealand, we could add our location, our internal geography, our overall approach to transport planning and provision, our very high rates of immigration and emigration leading to globally-dispersed families, the Treaty of Waitangi, and our relationship with the Pacific. The relative inequality of aviation compared to other forms of transport and to other sources of greenhouse gas emissions is also relevant: an industry that more heavily serves the rich is less defendable that one that serves people more equally.

The problem is not just that the high emitters have to pay more towards the transition, even more as a proportion of their income: that position is broadly accepted and is implemented in progressive income taxes. (For aviation, see Büchs and Mattioli (2022).) The harder problem is that they actually have to reduce their emissions. Ivanova and Wood (2020) report a target of 2.5 tonnes per person by 2030 as consistent with the Paris agreement. That means average emissions falling by 70%. But the bottom half of emitters can't reduce by very much at all, which means the top half have to do more. The situation is particularly extreme in aviation: only flyers can fly less, and only frequent flyers can fly a lot less.

The widespread realisation of ecological overshoot and its catastrophic consequences, as well as humanity's acceleration of unsustainable resource use when confronted with the reality of climate change, has prompted a wide range of responses (Murphy et al. 2021). An emerging body of work seeks to quantify the resource and energy use required for a commonly agreed decent standard of living (Grubler et al. 2018; Akenji et al. 2021). For example, the model of Millward-Hopkins et al. (2020) describes a lifestyle involving 5000–15,000 km of annual travel per person and energy consumption of 15 GJ/person/year, one-twelfth of New Zealand's present primary supply of 180 GJ/person/year.

Most modern economists and policymakers do not engage in the question of what consumption is luxurious, wasteful or unnecessary (Tilman 1999, Mitchell 2001). On the other hand, some go further and argue that overconsumption is built in to capitalism, and that therefore reducing emissions will require significant changes in work, production, consumption, advertising and social norms (Stuart et al. 2020). When presented with detailed information about the impact of flying and possible ways to address it, and having considered these in detail, the public include pricing measures and demand restraint in their preferred solutions (Büchs and Mattioli 2022). Our conclusion is that inequality and fairness are a central issue in addressing aviation emissions, and have resulted in numerous calls for measures to reduce the use of carbon-intensive luxuries (Baledón and Kosoy 2018, Chapman 2019, Gore 2020, Gössling and Humpe 2020, Ivanova and Wood 2020, Higham et al. 2021; Chancel et al. 2022; Cass and Lucas 2022).

6. Conclusion

The three main factors that will affect aviation emissions over the next 30 years are efficiency, alternative fuels and total travel. There is reasonable agreement that zero-tailpipe-emission aircraft will play a limited role in this time span. There is wide disagreement over the potential for alternative fuels and for the speed with which they can be supplied. Proposals rely on technology which is currently in insignificant commercial use, which makes estimating costs and risks difficult. The lifecycle emissions and renewable energy inputs to produce the fuels are also uncertain. The amount of SAF required depends on the amount of fuel required, i.e. on aircraft efficiency and total distance travelled. The total resources required for high growth, high SAF scenarios are very significant.

The past 2 years have seen a virtual revolution as numerous international bodies have aligned behind a vision of net zero aviation by 2050. The main areas of difference between industry- and non-industry-led scenarios is that the former involve more growth–indeed, they often consider growth rates as given and not as a key variable–and reject emissions pricing. Some industry proposals seek government funding and subsidies. Some also reject regulation and rely on voluntary action and aspirational goals. On balance, we find the high growth scenarios unrealistic, unjust and unsustainable. Traffic growth seems likely to defeat even the most ambitious and speculative technology scenarios.

The mitigation of aviation emissions is a challenging and (relative to the scale of the problem) understudied area. It combines the challenges common to many other areas of mitigation with notable ingredients of its own: technological challenges and uncertainty, internationalisation, a record of past traffic growth along with anticipated future traffic growth and a favoured cultural status. To these, other aspects are particularly relevant to New Zealand: the country's remote location, its very high proportion of globally dispersed families, its high level and rapid increase of flying, its tourist industry and its poor public land transport system.

Therefore, a complete solution is unlikely to be realisable or even foreseeable at present. Rather than prescribing solutions, the immediate focus as New Zealand prepares to revise its aviation emissions plan for ICAO should be to consider the process that is to be followed and how it balances and represents different interests. However, we do conclude, first, that the Avoid/Shift/Improve framework is relevant to every one of the topics we have touched on here and should form part of the overall approach, and, second, that investment in unsustainable capacity growth will form a key locus of attention in the immediate future. In place of the often-heard slogan that aviation emissions are hard to abate, we regard them as being hard to govern. A consequence of the processes that have dominated thus far is that the significant roles played by traffic growth and equity have been underemphasised.

Two key events of the past half decade reinforce the urgency of the task. The first is the proven ability of the New Zealand aviation industry to increase emissions at a staggering rate when unregulated, as observed from 2015 to 2019; the second is COVID, which grounded most flights. Ensuring that aviation emissions remain permanently well below 2019 levels requires urgent action. Bold action now would make the longer-term task significantly easier.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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