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A Policy-Sensitive High-Level Model for Comparison of Emission and Cost Reduction Options for Aviation

Techno-economic model for zero emission aviation in Norway

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Master thesis in Energy, Natural Resources and the Environment

NORWEGIAN SCHOOL OF ECONOMICS

> Development that meets the needs of the present without compromising the ability of future generations to meet their own needs.
>
> – Brundtland Report (1987)

Executive Summary

In Norway, aviation plays a central role in connecting the remote areas of the country with its cities, and is a fundamental means of transportation for the population to reach hospitals and educational institutions. Norway hosts half of the Nordic region's twenty-five busiest airports and the routes from Oslo to Trondheim, Bergen, and Stavanger are amongst the ten busiest in Europe. Norway also presents the largest Public Service Obligation (PSO) routes network, with forty-four airports owned by the government through its airport operator, Avinor. These characteristics, together with many small regional routes, make Norway potentially very suitable for the first pilots of emission-reducing options for aviation. Furthermore, in the eyes of its airport operator Avinor, Norway's geography makes its connected aviation network economically rational. With focus on Norway, this case-study evaluates the commercial feasibility of three aircraft identified to have near-term potential to reduce aviation emissions and costs – one hydrogen-electric, one hybrid-electric and one battery-electric aircraft – on three routes: Bergen-Stavanger, Trondheim-Bergen and Bodø-Leknes. In addition to presenting an emission and a cost model, the study proposes policy scenarios that aid in making emission reduction options more cost-competitive, and hence lead not only to reduced emissions but also to reduced costs. This study takes inspiration from a first 2020 University of California, Berkeley study on the potential for sustainable regional aviation (SRA) in California. The thesis also builds on a 2020 Western Norway University of Applied Sciences study of the potential of sustainable aviation in Norway on selected routes to be covered by aircraft with more emission-effective propulsion.

The model shows that based on modelled number of passengers and the technical data from company dialogues with Berkeley contributors, the ZeroAvia renewably–powered hydrogen–electric 19-seater HyFlyer can be more cost-competitive than the hybrid, the battery-electric aircraft and the traditional aircraft currently in use on the selected three reference routes, with cost-competitiveness over 90 to 100% of the studied aircraft. The renewably–powered hydrogen–electric aircraft is more emission-effective than the battery-electric based on modelled number of passengers and assumptions of hydrogen production from electrolysis in 2025 and more emission-effective than the hybrid-electric aircraft with on-site or nearby electrolysis plant. Including hydrogen fuel cells in the Norwegian mandate for sustainable aviation fuels can (a) strongly facilitate technology and industry development in Norway and (b) make more emission-effective aircraft even more cost-competitive.

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This is **for** and **thanks to all of you**. Thank you to my Academic Supervisor Stein Ivar Steinshamn for progressively welcoming my thesis topic and creating the space for me to research on a truly meaningful challenge. Thank you to my incredible Company Supervisor at ZeroAvia, Julian Renz, for providing the challenge and for your continuous support. These years your niece is young but I have hardly any doubt: she is already very proud of you.

For my parents and grandparents, who weren't born with a manual to be parents and have learnt life and parenting along the way. For all the years since I left Treviso, in which you've put the heart in your hands while thinking of me from afar. Thank you for your hard work testimony and the thousands of evenings I've seen you get dressed and head to the hospital and the farm for the night. Hard work is your legacy, which I'm honored to carry. For my sister. Thank you Ilenia. You've seen it all with me and I commend you for being the most courageous and understanding living being. This goes to all the years still ahead of us. May our sisterhood be as resilient as your heart. For my brother Denis. Thank you for your silent but ever present support during all these years. Your presence is light and hope.

Thank you to my Berchtolding Family. With you I flew for one of the very first times in my life. You are forever dearly remembered. Thank you to my Wannsee Family, the true hope of the past ten years of my life. Wannsee is now life. It is the place on the map, and most importantly in all our hearts, where Planet Earth really has no borders. Thank you to my European Solidarity Corps colleagues in Åmål and Säffle for the 2019 Earth Hour Ambassador experience and the chance to work in Sweden. To the UN Global Compact Norway Family. I am honored and grateful for having worked alongside you during my Master Program. Thank you for your responsibility testimony, progressiveness and the spaces you create daily for real and sustainable growth. Thank you to the RISE Community Family. This goes to the hundreds of mornings we're waking up early together and standing together for growth, gratitude and community. To my CEMS ESA Business Project Team and my USA Model UNFCCC Team for the honest work in these months, the space to complete this study and your understanding.

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1. Introduction

1.1. Problem Statement: Air transport in an emission world

During 99% of our history, humans have lived as **restless nomads**, challenging the concept of mobility for as long as one can remember (Service, 1968–85). Within these settings, humans have always embedded a **strong driving force for the development of mobility** and improvements in transportation technology have been among the most powerful drivers of change in our history. Advances in technology have made it possible for human beings to reach and explore farther areas, and expand their horizons. As new transport challenges arose and new inventions were applied to them, researchers have been working to find new ways to reduce costs and increase transport efficiency. Travel time has decreased and the ability to move more frequently and with larger loads has increased. Hunting-gathering and nomadic societies started to rapidly dissolve especially after the Industrial Revolution (Service, 1968-85). With it came unprecedented improvements, as well as unprecedented human impact and changes on Earth's climate system on a global scale. The immense human-led improvements came at the cost of burning fossil fuels – releasing significant amounts of carbon dioxide and other greenhouse gases (GHGs) into the atmosphere and „it would take several more decades before scientists realized the full extent of GHGs accumulation in the atmosphere, and their relation to global warming" but it is now clear that for several years "average surface temperatures have consistently surpassed 1.5°C above pre-industrial values" (Ghosh, 2021).

Global aviation has grown dramatically worldwide (Michot et al., 2003), with estimates that emissions have increased by a factor of 6.8 per year between 1960 and 2018 (Lee et al., 2020). In particular, according to Penner et al. (1999), global passenger air travel, as measured in revenue passenger-kilometer, has been projected to grow by about 5% per year, and total aviation fuel use – including passenger, freight and military – by 3% per year, "the difference being due largely to improved aircraft efficiency" (Penner et al., 1999). In fact, according to Vlek and Vogels (2000), substantial aircraft emissions per passenger-kilometer improvements have been made, with more fuel efficient aircraft engines resulting from the reduction of airframe weight. However, the authors asserted already in the year 2000 that these measures to increase aircraft fuel efficiency summed to the establishment of international emission regulations by ICAO were still insufficient to compensate for the increase in emissions as a result of the growth of global aviation (Vlek and Vogels, 2000).

With worldwide air traffic is expected to continue to grow at rates of 3-5% per year between 2020 and 2050 (ICAO, 2016a; Penner et al., 1999; Van Pham et al, 2010), and therefore the projected growth of aviation's environmental impacts, "decision-makers and stakeholders are seeking policies, technologies, and operational procedures that balance environmental and economic interests" (Mahashabde et al., 2011). In addition, according to Graver et al. (2019), by 2050 aircraft might account for 25% of the global carbon budget. Gössling and Humpe (2020) also estimate that only 2% to 4% of global population flew internationally in 2018, find that 1% of world population emits 50% of CO2 from commercial aviation, and reiterate that the current climate policy regime for aviation is inadequate. "If the global aviation sector were treated as a nation, it would have been the sixth-largest source of carbon dioxide emissions from energy consumption in 2015, emitting more than Germany (Air Transport Action Group [ATAG], 2019; Olivier et al., 2016)", write Graver et al. (2019).

Vlek and Vogels (2000) present three challenges to finding answers to the question of what measures shall be advised and adopted: (1) the international character of aviation implying that measures must be taken globally, (2) the variety of global aviation, with its many different kinds of aircraft, and large number of flights over a very wide range of distances and (3) the complexity of assessment of the many possible emission reduction measures, spanning from technical to economic measures. Similar categorizations of subsystems of measures (technology, economy, atmosphere and environment) can be found already in the AERO model by Vlek and Vogels (2000) as well as in the listed measures by ICAO and in Destination 2050, the route to net zero European aviation by the European aviation sector. The complexity of the topic motivates the use of a High-level Emission and Cost Reduction for Aviation (HECRA) Model. According to Eliassen and Stoknes (2015) in the Festschrift to Jorgen Randers, high-level modeling is an approach and research tool whose advantage is to make a synthesis of a large, often interdisciplinary body of research, allowing for both broad synthesis and in-depth empirical research.

A new generation of more emission-effective aircraft propulsion is challenging the norms of commercial air traffic. This study explores exactly how and with what options the aviation industry can reduce its costs and emissions by focusing on the following subsystems: (1) environment, (2) technology, (3) economy and (4) policy, with case study Norway.

Firstly, ***Chapter 2 Literature Review*** frames the current status of research on the topic by starting from (1) the main factors influencing the environmental impact of aircraft emissions, and following with presenting (2) the current emission reduction options from the *ICAO Global Coalition for Sustainable Aviation* as well as from *Destination 2050 – A route to net zero European aviation* by the European aviation sector. In addition, the chapter includes (3) a section on the state of the methodologies for evaluation of aviation options and (4) outlines the efforts of the Norwegian aviation industry in the last two decades by summarizing the measures included in the four reports published so far with the title "Bærekraftig og samfunnsnyttig luftfart", "Sustainable and socially beneficial aviation", in 2007, 2011, 2017 and 2020. Avinor, the Norwegian airport operator, led the work from report one to report four. Finally, the chapter presents (5) key insights from the four conferences the author of this study attended in 2020 and 2021 and from company dialogues with Avinor and the key contributors to the University of California, Berkeley Sustainable Regional Aviation study. The four conferences that were attended are the Norwegian Hydrogen Conference in June 2020, the ZeroAvia Conference in June 2020, the First International Hydrogen Aviation Conference in September 2020 and the Digital Half-day Webinar on Sustainable Aviation by the Department of Mechanical and Marine Engineering at the Western Norway University of Applied Sciences and the Bergen Energy Lab at the University of Bergen in October 2020.

Secondly, ***Chapter 3 Methodology*** presents the research design choices, the collected data types and the study's time horizon, including hypotheses and research model. Thirdly, ***Chapter 4 High-level Emission and Cost Reduction for Aviation Model, Data and Assumptions*** describes the subsections of the model: (1) environment, (2) technology, (3) economy and (4) policy. The chapter includes the explanation of the key assumptions and collected data in the various subsections.

Chapter 5 Results and Discussion follows to the model presentation by analyzing the collected data presented in the previous chapter and adding new perspectives that were not mentioned earlier in the thesis. Chapter 6 Policy Recommendations follows with policy improvements recommendations based on the current policies outlined in the four Sustainable and Socially-beneficial Aviation reports for Norway. Lastly, ***Chapters 7, 8 and 9*** address the reliability, validity, limitations and research ethics of the study, draw the conclusions and highlight suggestions for avenues for future research.

1.2. Research Aim and Research Questions

This paper seeks to reproduce and adapt to the Norwegian context a 2020 University of California, Berkeley study [Schefter et al. (2020), also called Berkeley model – University dialogue] on the potential for sustainable regional aviation (SRA) in California. In the Berkeley study and this Norwegian study, the authors evaluate the commercial feasibility of three aircrafts identified to have near-term potential to reduce aviation emissions and cost: ZeroAvia's 19-passenger hydrogen-electric aircraft, Faradair's BEHA_M1H 18-passenger hybrid-electric aircraft and Eviation's Alice 9-passenger battery-electric aircraft. The thesis also builds on a 2020 Western Norway University of Applied Sciences study on the potential of sustainable aviation in Norway on selected routes to be covered by aircraft with more emission-effective propulsion.

In the Berkeley model, the contributors evaluate the environmental and financial performance of the aircraft technologies, by selecting three Californian reference travel routes, conducting a mode shift analysis to compare against typical modal substitutes, and finally making policy recommendations. Similarly, this study evaluates the cost and emission reduction potential of the aircraft solutions identified in the Berkeley model by selecting three Norwegian reference travel routes and additionally includes an incentive model. This paper aims to answer the following research questions, with a specific focus on the Norwegian case study: (1) What types of aircraft solutions can make air travel more cost-effective and emission-effective? (2) What kind of policies can incentivize the development and adoption of the above identified aircraft solutions? The reproduction of the Berkeley study for Norway was commissioned by ZeroAvia, powering the world's first hydrogen fuel-cell-powered flight for a commercial-size aircraft in September 2020 (Cairns, 2020).

Figure 1. ZeroAvia's HyFlyer

Figure 2. Avinor numbers. From Avinor, The Full Story (2017)

Figure 3. Public Service Obligation (PSO) routes. From Avinor (March 2020) and NOU 2019:22

1.3. The Norwegian Case Study

In Norway, forty-four airports are owned by the government through its airport operator, Avinor, making the country one of the most hyper-connected aviation networks in the world, with half of the Nordic region's 25 busiest airports (Avinor's website, 2021). Norway is the country in Europe with the most airline trips per capita, and the routes from Oslo to Trondheim, Bergen, and Stavanger are all amongst the ten busiest in Europe (Visitnorway, 2020; Avinor, 2017). Furthermore, aviation in Norway is particularly important to connect the South of the country to the Northern areas (Lian, 2010). Very relevant for this study and the selected reference travel routes is the contribution by Lian (2010): "Due to the long stretched shape of the country and sparse population, many regions in Norway are dependent on air travel that involves chained trips with two or more legs. Northern Norway and the west coast are particularly dependent on such networks". According to the author, chained trips involving two or more legs account for 28% of domestic air travel in Norway (Lian, 2010).

A further reason why the Norwegian case is relevant is that four reports have been published so far with the title "Bærekraftig og samfunnsnyttig luftfart", "Sustainable and socially beneficial aviation", in 2007 (Lian, 2007), 2011, 2017 and 2020 (Avinor, respective years). The work on the 2020 report was led by Avinor, in collaboration with SAS, Norwegian, Widerøe, LO and NHO Aviation. The 2017 report asserts: "A new and modern aircraft fleet is the most important contribution to reducing greenhouse gas emissions from aviation - in short, the aircraft become lighter and the engines more efficient. New technology combined with phasing in [sustainable] fuels, and in the longer term, electric aircraft, will reduce emissions from aviation significantly". Fast forward to the 2020 report, much dialogue, work and research have been added to the main research questions of this paper: how to keep aviation emissions and cost levels effective, by looking into changing the type of aircraft technologies, fuels and policy measures. The 2020 report's goal is that the Norwegian aviation be fossil-free by 2050.

Figure 4. Four major markets: Oslo, Bergen, Trondheim and Stavanger. Avinor (2017). The Full Story.

2. Literature Overview

2.1. Environmental impact of aircraft emissions

According to the IPCC, emissions of CO2 from all transport sectors account for about 22% of all global emissions of CO2 from fossil fuel use (IPCC, 1996a). In 1990, aviation was responsible for about 12% of CO2 emissions from the transport sector (Faiz et al., 1996; IPCC, 1996b; OECD, 1997a,b). Consequently, aviation is currently responsible for about 2% of total global emissions of CO2 from the use of fossil fuels (Sprinkle and Macleod, 1993; WMO, 1995; Gardner et al., 1996). More recent facts and figures still report similar percentages.

Aviation emissions have occurred mainly since 1950 (Schumann, 1993), yet they are characterized by the long-term impacts from CO2 emissions and shorter-term impacts from non-CO2 emissions and effects, which include the emissions of water vapour, particles and nitrogen oxides (NOx). Figure 5 from Nelson and Reddy (2018) presents GHGs emissions subdivided in the three fundamental phases of flight:

Species	Idle	Takeoff	Cruise
CO_2	3,160	3,160	3,160
H_2O	1,230	1,230	1,230
CO	25 (10 to 65)	1	1 to 3.5
HC[a] (as CH_4)	4 (0 to 12)	0.5	0.2 to 1.3
NO_x			
Short haul	4.5 (3 to 6)	32 (20 to 65)	7.9 to 11.9
Long haul	4.5 (3 to 6)	27 (10 to 53)	11 to 15
SO_x (as SO_2)	1.0	1.0	1.0

[a]Hydrocarbons
Source: Vedantham, A. 1999. Aviation and the global atmosphere: a special report of IPCC Working Groups I and III. *http://repository.upenn.edu/library_papers/61* (accessed August 12, 2016).

Figure 5. GHGs per phase of flight, from Nelson and Reddy (2018)

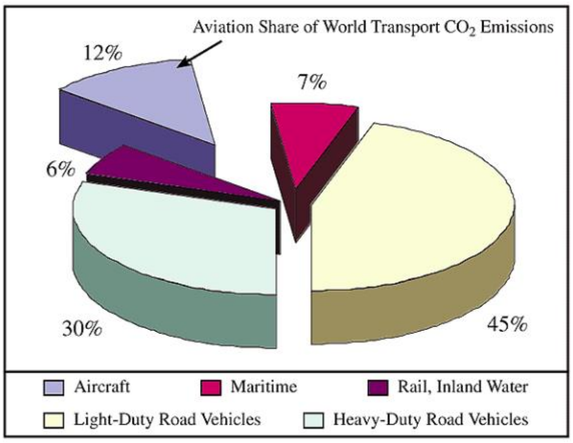


Figure 6. Share of aviation/transport emissions from Penner et al. (1999)

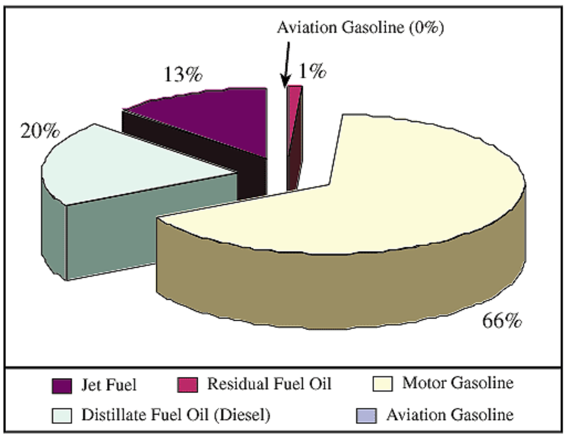


Figure 7. Share of aviation/transport emissions from Penner et al. (1999)

The four main factors (Janić, 1999) influencing aviation emissions include: (1) the intensity and volume of aircraft movements, (2) the type and spatial concentration and distribution of the particular pollutants, (3) fuel consumption and energy efficiency and (4) the rate of renewing of the aircraft fleet by introducing "cleaner" aircraft (Van Pham et al., 2010). Mahashabde et al. (2011) classify aviation environmental impacts as a combination of noise impacts, air quality impacts and climate impacts. The authors list air quality impacts as being provoked by the GHGs: nitrogen oxides, carbon monoxide, sulfur oxides and particulate matter. Climate impacts are provoked by the GHGs: carbon dioxide, water vapor, contrails and aviation-induced cirrus, sulphate aerosols and particulate matter, carbon monoxide and volatile organic compounds (Mahashabde et al., 2011). Given these important considerations, the study does not focuses only on the carbon footprint of aviation, but on its climate impacts in a broad spectrum, which are expressed in CO2 equivalents, also abbreviated as CO2-eq.

According to Gnadt et al. (2019): "An almost unique feature of aviation is that a significant portion of the aviation-attributable climate warming is due to non-CO2 emissions, especially contrails and contrail-cirrus clouds. Contrails are white, line shaped clouds that form behind aircraft. They have about the same order of magnitude of radiative impact as cumulative aviation-related CO2 emissions, with estimates ranging from 33% to 257% of the CO2 impacts on an absolute global warming potential basis for a 100-year time horizon" (Dorbian et al., 2011). "In contrast, aircraft that do not combust fuel and thus do not emit water vapor at high-altitude have the potential for greatly reducing the climate impacts of aviation" (Gnadt et al., 2019).

2.2. Mitigation: Emission reduction options

While aviation accounts for 2-3% of CO2 emissions globally, it accounts for around 3.8% of total CO2 emissions in Europe (European Commission, 2021). With findings such as Gössling and Humpe (2020)'s of the magnitude of 1% of world population emitting 50% of CO2 from commercial aviation, it comes as no surprise that one of the topics of major discussion in relation to measures to reduce aviation emissions is the reduction of air travels. In fact, if everyone in the world took just one long-haul flight per year, aircraft emissions would largely exceed the US's entire CO2 emissions, according to ICCT (Graver et al., 2019).

In the Norwegian case, which this case study focuses on, according to the Institute of Transport Economics, (Transportøkonomisk institutt, TØI): “Substituting air transport with land transport has a limited potential as only 6-8% Norwegian air travel, measured in passenger kilometres, take place on routes and distances where there are realistic alternatives” (Lian, 2007). Norway has a particular dependency on air travel. However, “it can help to tell others about your decisions to reduce flying”, writes Timperley for the BCC (2020). In the mentioned BCC interview, Cait Hewitt, Deputy Director of the Aviation Environment Federation (AEF), an environmental non-profitit states: “Making it known that you're someone who's given up flying for climate reasons can start to have a statistically significant impact on the amount that people around you fly. Offsetting just can't be a long-term solution” she says. Many people object to offsetting as it implies wealthier individuals can keep contributing to climate change without altering their behaviour (Timperley, 2020).

This chapter presents the current emission reduction options from the *ICAO Global Coalition for Sustainable Aviation* as well as from *Destination 2050 – A route to net zero European aviation.* As mentioned in the Introduction, the categorization of subsystems of measures technology, economy, atmosphere and environment can already be found in the AERO model by Vlek and Vogels (2000).

The following is the excerpt on emission reduction measures from ICAO’s Resolution A39-2: “The ICAO 39th Assembly recognized that the aspirational goal of 2 per cent annual fuel efficiency improvement is unlikely to deliver the level of reduction necessary to stabilize and then reduce aviation’s absolute emissions contribution to climate change, and that goals of more ambition are needed to deliver a sustainable path for aviation. To achieve international aviation’s global aspirational goals, a comprehensive approach, consisting of a basket of measures has been identified:

- Aircraft-related technology development – purchase of new aircraft and new equipment to retrofit existing aircraft with more fuel-efficient technology;
- Alternative fuels – investments in the development and deployment of sustainable aviation fuels (SAFs);
- Improved air traffic management and infrastructure use – improved use of communication, navigation and surveillance/air transport management (CNS/ATM) to reduce fuel burn;
- Economic/market-based measures – researching and building awareness of low cost, market-based measures to reducing emissions such as emission trading, levies, and offsetting” (ICAO, 2016b).

As stated from ICAO's website (2021), the main objective of the *ICAO Global Coalition for Sustainable Aviation* is to promote sustainable international aviation. "The ICAO Global Coalition for Sustainable Aviation includes stakeholders working on innovations and breakthroughs on aviation **Technology**, **Operations and Infrastructure**, and **Sustainable Aviation Fuels**, together with the CORSIA as the complementary measure to achieve the environmental objective.

Each of the three focus area of the coalition firstly aims to raise awareness of the continuing progress made towards in-sector CO_2 emissions reduction from international aviation, building on existing leaderships and champions, as well as strengthen existing partnerships and innovations" (ICAO, 2021b).

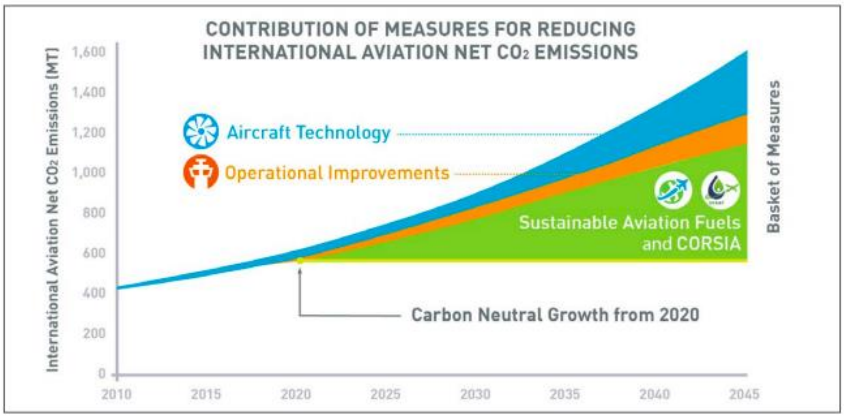


Figure 8: Basket of Measures Contribution for Reducing International Aviation Net CO2 emissions, from ICAO (2019)

Figure 9. ICAO Global Coalition for Sustainable Aviation, from ICAO's website (2021b)

It is important to underline that ICAO's 2016 basket of measures addresses CO2 emissions, but as presented in Chapter 2.1. with the contribution by Gnadt et al. (2019) as well as highlighted by Schäfer et al. (2019): "It is estimated that the non-CO2 warming impacts of aircraft are [at least] of the same magnitude as aircraft CO2 emissions, thus effectively [at least] approximately doubling aviation's contribution to climate change". To address such impacts, writes ICAO (2019), "the "IPCC Aviation and the Global Atmosphere report" (Penner et al., 1999) was written in 1999, which provided the scientific basis for impacts of aviation on the global climate. Twenty years after the publication of this report, these estimates of aviation climate forcing could be enhanced by a new international scientific assessment. In the absence of such a report, in order to update and strengthen the scientific base, the information contained in the IPCC 1999 report is being supplemented by the work carried out by ICAO and the Committee for Aviation Environmental Protection (CAEP)" (ICAO, 2019).

According to CAPA – Centre for Aviation (2021), Europe is leading world aviation towards net zero carbon emissions and bringing together European airlines, airports, Original Equipment Manufacturers (OEMs) and air navigation providers. According to the European timeline *net zero timeline*, the biggest contributor to emission reductions is improvements to aircraft/engine technology (37% of the total reduction, split between hydrogen powered aircraft 20%, and kerosene/hybrid electric 17%), followed by sustainable aviation fuels (34%).

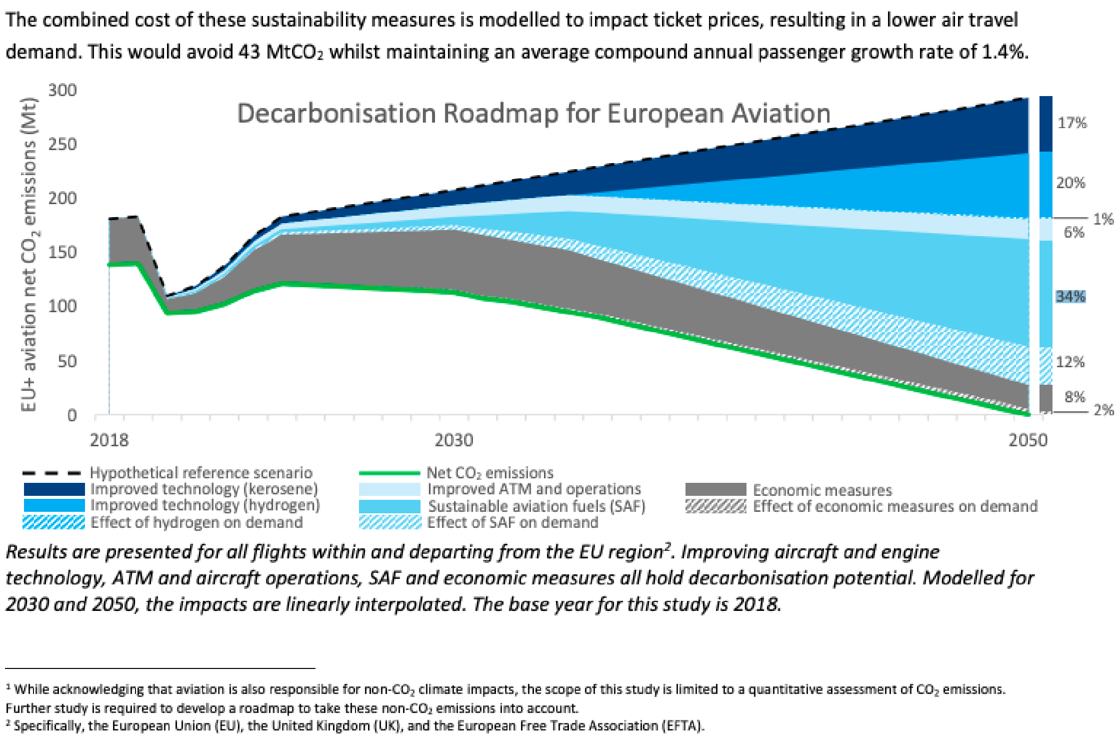


Figure 10. European Decarbonisation Roadmap (van der Sman et al., 2020)

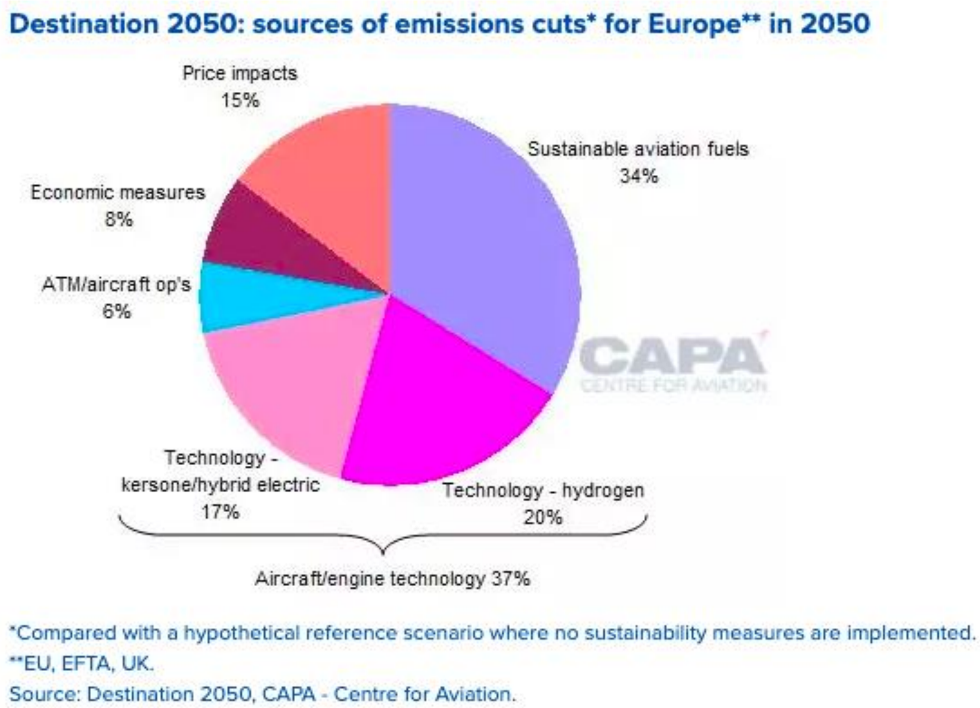


Figure 11. Pie Chart European Decarbonisation Roadmap (CAPA – Centre for Aviation, 2021)

However, also in the case of the European roadmap it needs to be emphasized that it is a decarbonisation roadmap. It acknowledges that aviation is responsible for non-CO2 impacts but limits measures to a quantitative assessment of CO2 emissions because further study is needed to develop a roadmap that take non-CO2 emissions into account. Due to this call for further scientific assessment, the 2020-2021 conferences described further on in this literature review, attended by the author of this study, cast further light on non-CO2 impacts estimations.

2.2.1. Aircraft and engine technology

According to CAPA – Centre for Aviation (2021), "technology is by far the most important overall factor for cutting carbon emissions, embracing both aircraft and engine technology and sustainable aviation fuels (SAFs)". This section focuses on aircraft and engine technology. The following section focuses more in particular on SAFs.

The authors Alvestad et al. (2020) conduct a first study of the potential of sustainable aviation in Norway on selected routes to be covered by aircraft with more emission-effective propulsion. In their study, sustainable aviation covers zero-emission propulsion systems for aircraft. "However, there has been little advance in the field of zero-emission technologies in the aviation sector compared to the present use of engines powered predominantly by petroleum-based fuel" (Alvestad et al., 2020), therefore the authors include also hybrid propulsion in their study, and present a list of current electric and hybrid electric aircraft projects. The list, presented in Table 1, encompasses aircraft powered by electric motors that can receive electrical energy from a secondary source such as a battery or a hydrogen fuel. The classification by Alvestad et al. (2020) is relevant for the present study since the latter seeks to reproduce and adapt to the Norwegian context the 2020 University of California, Berkeley study on the potential for sustainable regional aviation (SRA) in California by evaluating the commercial feasibility of three aircrafts identified to have near-term potential to reduce aviation emissions and cost: ZeroAvia's 19-passenger renewably-powered hydrogen-electric aircraft, Faradair's BEHA_M1H 18-passenger hybrid-electric aircraft and Eviation's Alice 9-passenger battery-electric aircraft. The thesis also builds on Alvestad et al. (2020)'s Western Norway University of Applied Sciences study on the potential of sustainable aviation in Norway since the authors focus on the second one of the three selected routes for this High-level Emission and Cost Reduction for Aviation (HECRA) Model: Bergen-Stavanger. In addition to Alvestad et al. (2020)'s technical feasibility analysis, the HECRA Model performs a cost analysis and a policy-related incentive analysis.

Table 1. Current electric and hybrid electric aircraft projects (Alvestad et al., 2020)

Name	Type	Seats	Country	First flight	Certified by
SkySpark	Hydrogen	1	IT	2007	N/A
Yuneec E430	Electric	2	CN	2009	2009
Solar Impulse II	Electric	1	CH	2009	2014
Volocopter Volocity	Electric	2	DE	2011	N/A
DA36 ESTAR 2	Hybrid Electric	2	AT	2011	N/A
eHang 184	Electric	1	CN	2015	-
Elektra Solar OPS One/Two	Electric	1 / 2	DE	2015 / 2011	N/A
Magnus-Siemens eFusion	Electric	2	HU	2016	-
Hamilton aEro 1	Electric	1	CH	2016	N/A
HY4	**Hydrogen**	**4**	**DE**	**2016**	**N/A**

Extra 330LE	**Electric**	**1**	**DE**	**2016**	**N/A**
Wisk Cora	Electric	2	US	2017	N/A
eHang 116/216	Electric	1 / 2	CN	2018	2019
Kitty Hawk Flyer	Electric	1	US	2018	N/A
Acubed Vahana	Electric	1	US	2018	N/A
Bye Aerospace eFlyer 2/ 4	**Electric**	**2 / 4**	**US**	**2018 / 2019**	**N/A**
Harbour Air DHC-2	**Electric**	**7**	**CA**	**2019**	**2021**
Ampaire Electric EEL	**Hybrid Electric**	**6**	**US**	**2019**	**2021**
H55 Bristell Energic	Electyric	2	CH	2019	2021
CityAirbus	Electric	N/A	FR/DE	2019	2023
Aurora PAV	**Electric**	**2**	**US**	**2019**	**2023**
ZeroAvia HyFlyer	**Hydrogen**	**6**	**US**	**2019**	**2023**
XTI TriFan 600	Hybrid Electric	6	US	2019	2024
Lilium Jet	**Electric**	**5**	**DE**	**2019**	**2025**
Kitty Hawk Heavyside	Electric	1	US	2019	N/A
Liaoning Ruixiang RX1E	Electric	4	CN	2019	N/A
VoltAero Cassio	**Hybrid Electric**	**4-9**	**FR**	**2020**	**2021/2022**
Zunum	**Hybrid Electric**	**12**	**US**	**2020**	**2023**
NASA X-57 Maxwell	**Electric**	**N/A**	**US**	**2020**	**N/A**
Airbus E-Fan X	**Hybrid Electric**	**~100**	**FR**	**-**	**-**
Autoflight X V600	Electric	2	DE	2022	2025
Jaunt Air Mobility	**Electric**	**N/A**	**US**	**2022**	**2025**
Scylax E10	**Electric**	**10**	**DE**	**2022**	**2027**
EcoPulseTM	Hybrid Electric	N/A	FR	2022	N/A
Pipistrel Alpha Electro	Electric	2	SI	N/A	2015
Skai	**Hydrogen**	**5**	**US**	**N/A**	**2020**
Eviation Alice	**Electric**	**9**	**IL**	**N/A**	**2021**

Joby Aviation S4	**Electric**	**5**	**US**	**N/A**	**2023**
Overair butterfly	**Electric**	**4**	**US**	**N/A**	**2023**
Project Fresson	**Hybrid Electric**	**9**	**UK**	**N/A**	**2023/2024**
Heart Aerospace ES-19	**Electric**	**19**	**SE**	**N/A**	**2025**
Wright Electric 1	**Hybrid Electric**	**186**	**US**	**N/A**	**2030**
Boeing Sugar Volt	Hybrid Electric	N/A	US	N/A	2030-2050
Bell Nexus 6HX	**Hybrid Electric**	**4**	**US**	**N/A**	**Mid-2020s**
NASA CHEETA	**Hydrogen**	**N/A**	**US**	**N/A**	**N/A**
Pipistrel 801 eVTOL	**Electric**	**5**	**SL**	**N/A**	**N/A**
Airbus/ Audi Pop.Up	Electric	2	FR/DE	N/A	N/A
EmbraerX DreamMaker	**Electric**	**5**	**BR**	**N/A**	**N/A**
Dufour aEro 2	Hybrid Electric	2	CH	N/A	N/A
Volta Voltaré DaVinci	Hybrid Electric	4	US	N/A	N/A
Elektra Solar Trainer	Electric	2	DE	N/A	N/A
Breezer/ eCap	Hydrogen	1	DE	N/A	N/A
Avions Moubossin	Hydrogen	2	FR	N/A	N/A
NASA STARC-ABL	Turbo electric	N/A	N/A	N/A	N/A

The analysis of the three aircraft on additional routes with respect to the California area can serve as a contribution towards the literature on solutions to address the climate crisis in the aviation sector. Finally on the technology and manufacturers' perspective, a very insightful presentation was held on December 7th 2005 at the International Civil Aviation Day (ICAO, 2005). Under the Manufacturers' Multiple Paths & Opportunities to reduce Emissions listed are opportunities around: (1) the propulsion system, (2) aircraft materials, (3) structure, aero and systems design and methods, (4) manufacturing processes and (5) aircraft systems.

2.2.1.1. ZeroAvia's HyFlyer

ZeroAvia is a British/American hydrogen-electric aircraft developer. As can be seen from Table 1, ZeroAvia's currently working for certification of its 6-seater and 19-seater HyFlyer by 2023 – early 2024. In fact, ZeroAvia secured £12.3m in funding from the UK government through the ATI Programme to deliver a 19-seat hydrogen-electric powered aircraft that is market-ready by 2023 – the HyFlyer II project (Calderwood, 2020).

In addition to reduced emissions, “the novel zero-emission powertrain has 75% lower fuel and maintenance costs, resulting in up to 50% total trip cost reduction” (ZeroAvia, 2021). “In less than four years, ZeroAvia has gone from testing aircraft parts in pickup trucks to gaining the support of the UK government, and attracting investment from Jeff Bezos and Bill Gates to British Airways” (Harris, 2021).

2.2.1.2. Faradair’s BEHA_M1H

Faradair is developing a hybrid-electric aircraft concept that solves three core problems hindering regional flight growth: emissions, noise and operating costs (Faradair, 2021). According to the Berkeley University’s study (University dialogue based on company dialogue, 2020), this aircraft has a design with “triple box-wing” and solar panels, and the company strives to have flight trials in 2022. The aircraft is designed for regional flights.

2.2.1.3. Eviation’s Alice

According to the company website (Eviation, 2021), “Alice is the world's first all-electric commuter aircraft, built to make flight the sustainable, affordable, quiet solution to regional travel”. As can be seen from Table 1, Eviation strives for certification already in 2021.

2.2.2. Sustainable Aviation Fuels (SAFs)

According to Ekici et al. (2020): “Alternative fuels could be used to reduce the emissions of reaction engines used in aviation, but the use of alternative fuels has reduced the propulsion force, one of the most important performance parameters in aviation”.

There is an important distinction to be made between biofuels and electrofuels under the SAFs categories, which is also addressed by the Norwegian aviation industry in the 2020 report “Aviation in Norway – Sustainability and social benefit”: “Sustainable fuels such as biofuels and e-fuels (synthetic fuels) can be used directly in existing aircraft fleets and infrastructure, and is a turnkey solution to reducing greenhouse gas emissions from air travel. Norwegian aviation has been pioneering the adoption of jet biofuels. From 2020, Norway is the first country in the world to have a blending mandate for advanced biofuels in aviation. Norwegian airlines have plans for increased phasing in of sustainable fuels, and the Norwegian authorities have signalled a target of 30 per cent biofuel in aviation by 2030” (Avinor et al., October 2020). The report asserts that Avinor and NHO Luftfart, the section of the aviation industry of the Confederation of Norwegian Enterprise (NHO), Norway's largest organisation for employers and leading business lobbyist, conducted an analysis of local biomass for the establishment of large-scale production of biofuels for aviation in Norway. The analysis concluded that waste and by-products from forestry could provide enough biomass for 30 to 40% of the fuel demand for Norwegian aviation. This study aims to address the environmental impact of SAFs, considering that the second studied aircraft, Faradair's BEHA_M1H, is to be powered partially by SAFs.

With regards to e-fuels, the mentioned report asserts that it is Norwegian aviation's view that e-fuels delivered to aviation must be produced in a sustainable way. In this context, a very interesting application is the one of the AIR TO FUELS™ Technology by the company Carbon Engineering. Using this approach, Carbon Engineering can produce renewable fuels that are drop-in compatible with today's infrastructure and engines and are almost completely carbon neutral. "The process integrates four growing fields – renewable electricity generation, Direct Air Capture, clean hydrogen production, and sustainable fuel synthesis – to deliver a highly scalable, clean fuel solution" (Carbon Engineering, 2021). "The hard part is getting to carbon neutral Fischer–Tropsch. Once there, is easy to do refining to get to fully compatible commercial products including aviation kerosene or diesels" (Carbon Engineering company dialogue, 2019).

Similarly, according to Avinor et al. (2020)'s report, projects for the production of e-fuels are also being developed in Norway. "In June 2020, Norsk E-fuel presented plans for the construction of a production plant at Herøya. In the first facility, most of the CO2 will come from an industrial emission source, but it is also planned that a proportion of the CO2 will be captured from the air (DAC). The plan is to gradually increase the proportion of CO2 captured from the air in later projects. At the moment, e-fuels do not fall under the blending mandate for advanced biofuels" (Avinor et al., 2020). This element will be addressed under the policy recommendations of the present study.

2.2.3. Operations

"Improvements in air traffic management and aircraft operations are expected to be an important **short to medium term** source of cuts in carbon emissions, pending bigger step changes from technology. The biggest impact would come from the completion of the Single European Sky. Improved efficiency of Air Traffic Management (ATM) and the decarbonization of ground operations, including electric towing and taxiing of aircraft, are also important elements" (CAPA – Centre for Aviation, 2021).

ICAO's presentation with focus on the Manufacturers' Perspective at the International Civil Aviation Day (ICAO, 2005) also included insights on the opportunities to reduce emissions within operating procedures. The main ones are related to: (1) weight reductions because some procedures are linked within minimizing maximum takeoff weight (MTOW), (2) aerodynamic and engine performance improvements because based on aircraft and engine performance, several procedures can optimize operations, (3) optimized ground and flight, and maintenance procedures.

2.2.4. State Action Plans and Economic Measures

In 2020, ICAO launched the State Action Plan initiative as a means to provide States with the capacity and tools to take action in terms of policy development and standards setting to limit and reduce the impact of aviation on the global climate, especially geared towards ICAO Member States not having the human, technical and financial resources to do so. This initiative enables all ICAO Member States to establish a long-term strategy on climate change for the international aviation sector, involving all interested parties at national level.

The European Union has specific economic measures in place under this emission reduction measure type, with the European Emission Trading Scheme (EU ETS) being the mechanism that is implemented and complemented by the ICAO CORSIA scheme for international flights (van der Sman et al., 2020).

2.2.5. CORSIA

The ICAO's global Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) work was started in 2016. In Europe, aviation has been part of the EU ETS since 2012 for emissions until 2016. The EU ETS has therefore maintained its geographical scope limited to intra EEA flights from 2017, while the ICAO was developing CORSIA to start in 2021, and the reference emissions for CORSIA were intended to be the ones of 2019 and 2020.

The scheme will not include private jets or military planes. All in all, CORSIA will not require airlines to offset flight emissions for the six years of its first phase and will cost them less than 1% of operating costs by 2035, a DW analysis found (Deutsche Welle, 2021).

As this chapter presented, because technical and operational measures had proved inadequate to counter traffic growth, finally in October 2016 ICAO adopted a framework for a market-based measure. Today, “the Carbon Offset and Reduction Scheme for International Aviation (CORSIA) is the primary emission-mitigation tool for international aviation. It aims at ‘carbon-neutral growth’ from 2020 onward. Yet, even with an increased use of alternative fuels and comprehensive implementation of CORSIA, ICAO’s basket of measures will not produce a reduction in global aviation emissions” (Lyle, 2018). The author’s input to CORSIA is the proposal of a derivative but more ambitious strategy. “This would include incorporation of international aviation emissions in the Nationally Determined Contributions (NDCs) of Parties to the Paris Agreement and a more direct role for the United Nations Framework Convention on Climate Change (UNFCCC) in determining eligibility of emission units and alternative fuels, with the ICAO remaining accountable for monitoring, reporting and verification” (Lyle, 2018).

2.3. State of the methodologies for aviation options evaluation

At least two models for evaluation of aviation options in this context are fundamental to mention: the Aviation Emissions and Evaluation of Reduction Options (AERO) Model (Vlek and Vogels 2000; Michot et al 1993) and the Global Aviation Industry Dynamics (GAID) Model (Sgouridis et al, 2011).

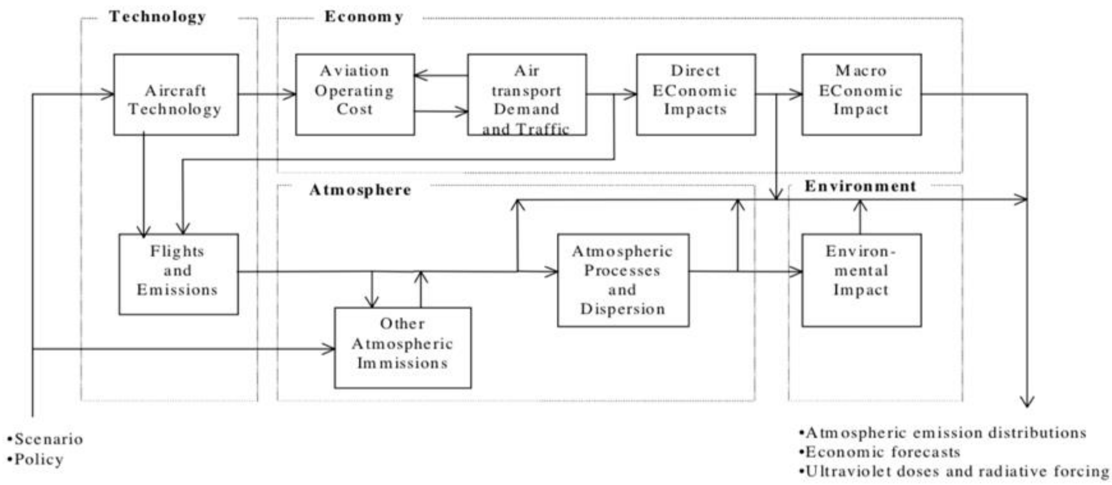


Figure 12. AERO Model Representation

The GAID model captures the behaviors of the three primary stakeholders in the global aviation industry; passengers, airlines, and aircraft manufacturers (Sgouridis et al, 2011).

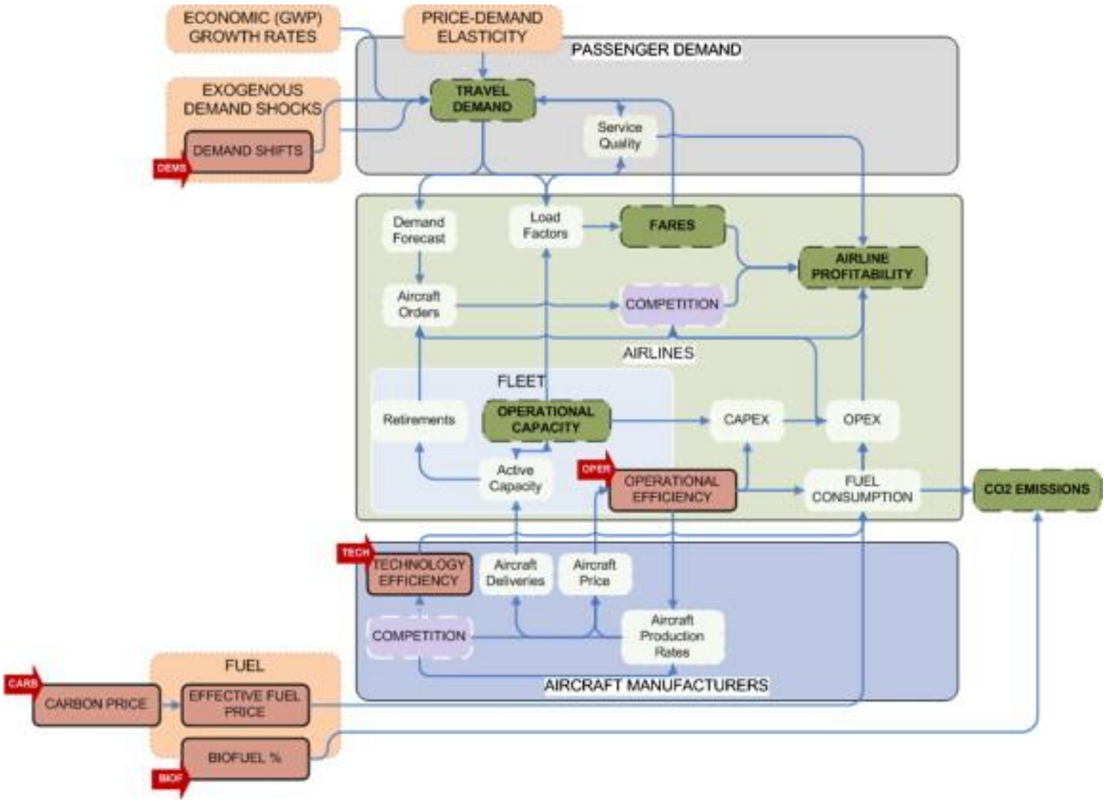


Figure 13. GAID Model Representation

In addition, as mentioned in the Introduction, the present study builds on the 2020 University of California, Berkeley study on the potential for sustainable regional aviation (SRA) in California and on Alvestad et al. (2020)'s Western Norway University of Applied Sciences study on the potential of sustainable aviation in Norway focusing on the route Bergen-Stavanger.

The 2020 University of California, Berkeley SRA study was conducted by seven contributors, and built on a previous life-cycle assessment study by one of the main authors, in collaboration with further contributors. According to the Berkeley contributors, of particular importance for short-haul regional aviation is the fact that it is inherently inefficient and sensitive to fuel prices because there are fewer miles to average out the takeoff and landing phases of flight. Their study on sustainable regional aviation is very relevant for Norway, since about one third of emissions in the airline industry are generated by short-haul flights of less than 1,500 kilometers (Graver et al., 2019) and "the shortest routes - sub-600 nautical flight miles - represent about half of global departures, with an outsize environmental impact" (Irfan, 2019).

To the relevance of the present study is the route choice chapter of the Berkeley study. The Berkeley study's approach to select which routes to model was to select a specific route as a case study for each of three different types of city pairs in California:

- Large metropolitan area to large metropolitan area: This category is served by major carriers. The contributors chose Oakland to Burbank as the specific case for this route type, specifically avoiding other airports such as San Francisco (SFO) and Los Angeles (LAX) to lower estimated airport fees.
- Metropolitan area to small town: The contributors chose Sacramento to San Luis Obispo as the case study for this route type because of Sacramento's status as the state capitol. They saw a need to connect it to smaller towns across the state and chose San Luis Obispo in particular to connect the research community at Cal Poly to the State's Government.
- Large metropolitan area to leisure location: The contributors chose San Jose to South Lake Tahoe as the case study for this type of route given the large number of tech workers who live in the South Bay and who travel for leisure to the Tahoe area.

For each of these route types, current modes and passenger volumes were estimated and CO2-eq emissions were calculated.

As mentioned in Chapter 2.2.1, Alvestad et al. (2020) focus especially on the Technology subsystem by conducting a case study on an hypothetical sustainable route between Bergen and Stavanger, in addition to an exceptional literature review on current projects and the technological status, with focus on batteries, hydrogen and biofuel. In their literature study conclusion, the authors highlight that biofuels can be a short-term compromise, however, not a permanent solution. They also emphasize that battery technologies are "potentially decades away before being commercially available" (Alvestad et al., 2020). In terms of infrastructure, the authors also mention the relevant project Elnett21, which has been planned to start in 2019 and end in 2024. The estimated budget of the project is 110 million NOK, of which Enova contributes 40 million NOK to Elnett21. Key partners are Avinor, Forus Næringspark, Lyse Elnett, Smartly and Stavangerregionen Havn. With the project at Stavanger Airport Sola, Avinor is planning to build a solar park and they hope the rest of the country will look at their solution for local electricity production in the airport area (Elnett21, 2021).

2.4. Norwegian Sustainable Aviation 2007-2021

"By 2040, Norway has promised all of its short-haul flights will be on electric aircraft. This could revolutionise the airline industry", writes Dowling for the BCC (2018).

The first report by the Norwegian aviation, released in 2007, already described a number of offensive measures to reduce the negative environmental impact of Norwegian aviation. The report highlighted that Norway is particularly dependent on air transport due to long distances both domestically and to the European continent, and that the country's topography makes it expensive to build roads and railways. In addition, it analyzed two fundamental aspects of air transport: its economic and social benefits on the one hand, and the environmental impact on the other. As mentioned earlier in this chapter, key insights from this report were that substituting air transport with land transport has a limited potential in Norway as only 6-8% of Norwegian air travel, measured in passenger kilometres, takes place on routes and distances where there are realistic alternatives.

The second industry-wide report published by the Norwegian aviation, released in 2011, saw some of the assumptions in the earlier report being changed due to more experience gained by the industry in the course of the three years. The report provided an updated description of the facts about greenhouse gas emissions from aviation and presented new measures. In particular, in 2011 Norway entered into an agreement with Finland, Estonia, and Latvia concerning the establishment of a common airspace block – the North European Airspace Block (NEFAB) – with the purposing of providing more efficient use of the airspace for the airlines. One of the important 2011 additions was the introduction of biofuel in aviation. According to the report, the ability to add sustainable, synthetic biofuel could significantly increase the potential for emissions reductions and Avinor and the industry were going to conduct a feasibility study to look at different alternatives, with authorities, research institutions and business invited to participate in the project. Based on the expected growth in traffic and flight distances, and assuming that the measures in the report were implemented, the following conclusions could be drawn: lower domestic emissions in 2025 than in 2007, however increasing international emissions in the period up to 2025, emissions could stabilise at around the 2007 level in 2025, but air traffic, measured in passenger kilometres, to increase by more than 97% between 2007 and 2025, and finally large proportion of emissions caused by the growth to be compensated for by the measures discussed in the report, with access to biofuels and the availability on the market of a new generation of aircraft with the expected energy efficiency.

In the third report, released in 2017, Avinor and the Norwegian aviation set a target for 30% of all aviation fuel sold at its airports to be sustainable biofuel by 2030. This is equivalent to a volume of approximately 400 million litres of jet fuel per year. In the spring of 2017, Rambøll, Vista Analyse and SINTEF looked into options to import jet biofuel and the potential of producing it in Norway. Their conclusion was that eventually there will be sufficient jet biofuel in the international market to achieve this target. There may also be sufficient biomass available from Norwegian forests to produce up to 500 million litres of sustainable jet biofuel, and it will be possible to produce this fuel in Norway.

Finally, the last report, released in October 2020, following to a report with the recommendations for electrified aircraft introduction, forecasts that traffic is expected to return to 2019 levels by 2024 due to the coronavirus pandemic. From then to 2050, the forecast is 0.7% growth for domestic traffic and 2.5% for international traffic. According to the report, in the longer term, low-emission solutions can reduce both costs to the environment and the airlines' operational and maintenance costs. Norwegian aviation believes that it can bring significant advantages to society if targeted measures to phase out fossil fuels are initiated now:

- Norway has a major competitive advantage for value creation and industry establishment within sustainable fuels, hydrogen and electrification;
- A transition to fossil-free aviation will secure jobs in the aviation, export and tourism industries, and for business in general;
- Technological development in aviation takes time; a challenging and ambitious decarbonization effort requires predictability and a long planning horizon;
- Norway is the first country in the world to implement a blending mandate for sustainable jet biofuels for civil aviation, with effect from 2020 and the Norwegian parliament has established a target to reach 30 per cent by 2030;
- Electrification will further reduce the use of fossil fuels, and Avinor and the Norwegian Civil Aviation Authority have prepared a program proposal for the introduction of electrified aircraft to Norway. A target of fossil-free aviation by 2050 is a confirmation that the industry wants to phase in sustainable fuels and electrified aircraft at an ambitious but realistic pace.

2.5. Key 2020-2021 Conferences and Company Dialogues

To obtain industry insights, during the study period the author attended five conferences and talks and engaged in company dialogues with Avinor, the key contributors to the University of California, Berkeley Sustainable Regional Aviation study, as well as aircraft manufacturers, including Boeing and Airbus. The four conferences that were attended are: (1) the Norwegian Hydrogen Conference in June 2020, (2) the 2020 ZeroAvia Annual Sustainable Aviation Summit in June 2020, (3) the First International Hydrogen Aviation Conference (IHAC) in September 2020, (4) the Digital Half-day Webinar on Sustainable Aviation by the Department of Mechanical and Marine Engineering at the Western Norway University of Applied Sciences and the Bergen Energy Lab at the University of Bergen in October 2020.

The Norwegian Hydrogen Conference saw the launch of the Norwegian Hydrogen National Strategy. Norway has set the goal to become a low emission society by 2050. The government has a target for greenhouse gas emissions in 2050 to be reduced by between 90 and 95 per cent compared to 1990 levels. The hydrogen strategy has been developed as a contribution to the process of developing new low emission technologies and solutions. The strategy lays the foundation for the government's future work with hydrogen. The main elements of the hydrogen strategy include a desire by the Government to prioritise efforts in the areas in which Norway has a particular advantage and can influence development, and where there are opportunities for increased value creation and green growth. The steps to make hydrogen a viable zero emission solution include making it safe and accessible both technologically and financially. Due to the current cost of storing hydrogen as well as its energy losses, clean hydrogen is currently not as profitable as other (more polluting) sources of energy. To make hydrogen more competitive and to attain the low emission goals for 2050, the Government will increase the CO2 tax by five percent every year until 2025.

In addition, to stimulate the necessary technological developments, the Government will, through current policy instruments, continue to support the necessary technological developments. The authorities will monitor developments and adjust the policy instruments if needed. The Government will in conjunction with the Climate Plan for 2030 evaluate policy instruments to promote the development and use of hydrogen in Norway. Furthermore, the Government will continue to support research into, and the development and demonstration of hydrogen technologies through relevant schemes, with a focus on projects of a high scientific quality and potential for commercial development. To make clean hydrogen more competitive on the market, hydrogen needs to be cheaper to produce. To tackle this, the Government will contribute to developing technology for the capture, transport and storage of CO2, and has ambitions to build cost-effective solutions for full-scale carbon capture and storage (CCS) plants in Norway, given that this will generate technology development in an international perspective. CCS is essential for the production of clean hydrogen from natural gas. Finally, in Norway, electricity used to produce hydrogen through electrolysis is currently exempt from the consumer tax on electricity. This helps to reduce the cost level at which hydrogen becomes competitive compared with other energy carriers. In 2020, the consumer tax on electricity was NOK 0.1613/kWh. In connection to the above exemptions, hydrogen vehicles get the same tax breaks and user benefits as those of battery electric vehicles.

The 2020 ZeroAvia Annual Sustainable Aviation Summit was hosted by ZeroAvia and held on June 25th 2020. The seminar was composed of two panels with four speakers each.

The first panel of the conference titled ‘Challenges and New Policies Post-COVID towards Sustainability at Scale in Aviation’ was moderated by The Times, and addressed how we can reach sustainability at scale in the aviation industry, coming out of the current economic context, and explored what mechanisms are available today, and which policies, technologies and practices should be implemented moving forward.

The second panel titled ‘Which new technologies can be deployed in the next five years and can inform post-COVID roadmaps?’ was moderated by Aviation Week, and saw the speakers addressing how technology development within the aviation space is moving us towards a more sustainable aviation future already today, with impacts before mid-decade.

The First International Hydrogen Aviation Conference (IHAC 2020) was organised by Hy-Hybrid Energy and held on September 3rd 2020. Hy-Hybrid Energy is a clean energy company focusing on integration of different energy systems to get the optimum performance, efficiency and cost benefits and specialist in all major fuel cell types, renewable energy systems, hydrogen storage and production. Main partners of the conference were Goldi Mobility, Hy-Hybrid Energy, Skycorp, ZeroAvia, AeroDelft, HyPoint, Doosan, Emec Hydrogen, Electrofluid. The seminar was characterized by four main sessions with five presentations each.

The first session was chaired by SKYCORP, and saw the following five presentations: (1) Hydrogen Energy - At the Heart of the Energy Transition, both on Ground and in the Sky by Air Liquide advanced Hydrogen Energy World Business Line, (2) Preparing for a hydrogen propelled aviation industry by Fuel Cells and Hydrogen Joint Undertaking (FCH JU), (3) Getting ready for new things in the air - A Scandinavian perspective Swedish Aviation Industry Group, (4) Preparing for a hydrogen future: a clean, green and more sustainable vision by ZeroAvia, and (5) What is needed to safely fly on hydrogen in the future, by the NLR-Royal Netherlands Aerospace Centre.

The second session was chaired by NLR-Royal Netherlands Aerospace Centre, and saw the following five presentations: (1) ‘Emission free electric flight with hydrogen- update on first hydrogen passenger aircraft Hy4’ by DLR, (2) ‘Why drones are the next best thing since the invention of aviation?’ by SKYCORP, (3) ‘Hydrogen (H2) Fuel Cell Powered Flying Wing Package: Drones and Air Taxis with PLASMA Flow Control and Bionic StingRAY Geometry – H2PLASMARAY’ by Electrofluidsystems, (4) ‘Hydrogen aircraft and the future of aviation’ by AeroDelft, and (5) ‘What does hydrogen offer the aviation industry?’ by Roland Berger.

The third session was chaired by CALAMALO Aviation SAS, and saw the following five presentations: (1) ‘Let’s hydrogenify transportation – so many opportunities, but where to start?’ by Rolls Royce Electric and Independent Consultant for Electric Mobility and Hydrogen Transition, (2) ‘Liquid Hydrogen: the Ultimate Sustainable Jet Fuel for a Zero Emission Aviation. Ongoing Work at Air Liquide for Flying a Representative Demonstrator Aboard a Manned Aircraft’ by Air Liquide advanced Technologies, (3) ‘Dual use of hydrogen for airships of the next generation’ by Atlas LTA Advanced Technology, Ltd, (4) ‘Hydrogen for lift and propulsion of cargo airships’ by Buoyant Aircraft Systems International, and (5) ‘Nearest term application of Hydrogen in Aviation – Sustainable Aviation Fuel Production’ by Commercial Aviation Alternative Fuels Initiative (CAAFI).

The fourth and final session was chaired by Rolls Royce Electric & Independent Consultant for Electric Mobility and Hydrogen Transition, and saw the following five presentations: (1) ‘How to make the Morgann greener with H2 propulsion?’ by CALAMALO Aviation SAS, (2) ‘Electrical propulsion architecture based on Hydrogen Fuel Cells for future large capacity airship solutions’ by Flying Whales, (3) ‘Powertrains for the air transportation market: Hydrogen vs. Lithium – what’s better?’ by Hypoint, (4) ‘H2 Clipper: The Practical Solution for the Hydrogen Economy’ by H2 Clipper, Inc, and (5) ‘Solid-State Electric Source for Powering Aircraft, With Major Flight Range Extension (Recorded Presentation)’ by Space Charge LLC.

The 2020 Digital Half-day Webinar on Sustainable Aviation was organised by the Department of Mechanical and Marine Engineering at the Western Norway University of Applied Sciences and the Bergen Energy Lab at the University of Bergen and held on October 7th 2020. The seminar saw five main presentations: (1) Emission free hydrogen electric propulsion for aircraft applications by the German Aerospace Center, (2) Environmental and Economic Aspects of Aviation Biofuels by the Technical University Hamburg-Harburg/Germany, (3) Electrification of aviation: accelerating the transition, by Avinor, (4) Electrifying aviation, demonstrator programmes and ambitions for the future by Rolls Royce Electric Norway AS and finally (5) Battery technology for electric aviation by Corvus Energy. The 2020 Western Norway University of Applied Sciences study on the potential of sustainable aviation in Norway on selected routes to be covered by aircraft with more emission-effective propulsion was also presented at the seminar.

During the Avinor segment, the representative underlined the following aviation emission reductions options, presented earlier in this literature review: more energy efficient aircraft, Sustainable Aviation Fuels (SAF), under which both jet biofuels and e-fuels, and of course electrification and hydrogen under new technologies. On the regional space, Avinor highlighted that hybrid-electric and/or fuel cells also have potential and that short routes can be flown 100% electric. Electrofuels are highlighted as having potential for long-haul flights by the Avinor presentation. According to Bergthorson (2018): “Today, hydrogen and synthetic hydrocarbon fuels are the most widely discussed electrofuel options”.

Finally, Avinor linked the electrification page of the website during the presentation, where relevant insights for this study can be found, for example in relation to Widerøe’s statements. Indeed, Avinor’s page presents the following statement Widerøe’s CEO: “Widerøe has to find a new aircraft type for short runway airports before 2030. By 2040 we have to replace around 30 aircraft. We’re looking for concepts that have zero emissions and lower operating costs. If we succeed, we can further develop the valuable public transport system we have developed in Norway over several decades. So far, we have not seen any challenges that cannot be solved” (Avinor, 2021).

3. Methodology

3.1. Research Design Choices, Data Type and Time Horizon

3.1.1. Research Design Choices

The study has a combination of exploratory and evaluative purposes. It is exploratory as the intent is to gain insights about what types of technical solutions and policy initiatives for Norway can reduce costs and impact of air travel on the environment. In addition, the study is evaluative because the effectiveness of current aircraft technologies is evaluated and comparisons are made among aircraft technologies based on their cost and emission effectiveness. The study makes its theoretical contribution by placing emphasis on understanding 'how effective' the solutions are, based on the technical, environmental and financial analysis. The study uses a mixed-methods research design as it makes use of both qualitative and quantitative methods to collect data. The qualitative data collected at conferences allowed the author to get a deeper understanding of the Norwegian context and aviation industry as well as its supply chain. In particular, the mixed methods research method is a sequential exploratory design, which involves more than one phase of data collection and analysis. The research design uses a qualitative method followed by a quantitative method, in order to expand and elaborate on the initial set of findings. Data was gathered through reports and conferences as well as company dialogues with several key appointment holders in the airport and aircraft companies to understand the Norwegian context (qualitative method). From there, quantitative data was collected on the fleet of the airlines offering service for the studied routes, building on the information obtained through the conferences and company dialogues. The thesis makes use of a case study strategy. This allows to generate insights from research using a context that is closer to reality (Saunders et al., 2016). As previously stated, the model focuses on the different modes on the routes (1) Trondheim-Bergen, (2) Bergen-Stavanger, (3) Bodø-Leknes. These routes were chosen since the Berkeley model, whose route selection was a case study of three different types of city pairs, is being reproduced and adapted here to the Norwegian context. The three different types of city pairs selected in the Berkeley model were (1) two large metropolitan areas, (2) metropolitan area to small town and (3) metropolitan area to leisure location. City pairs with similar characteristics (to the extent possible, since there are no large metropolitan areas in Norway) were chosen in Norway to allow for a margin of comparison with the original model. Following a consultation and company dialogue within Avinor's Carbon Reduction Programme, Bergen-Stavanger and Trondheim-Bergen were identified to be the most similar city pair to route (1) in the Berkeley model, due to the fact that especially Bergen and Stavanger have big company offices fairly close to the airports (Avinor company dialogue, June 30, 2020). Furthermore, airlines would need technical bases for the aircraft. Widerøe, the largest regional airline operating in the Nordic countries, has a base in Bergen and in Stavanger there is a big community of skilled people who have been working at aircraft maintenance (Avinor, personal communication, June 30, 2020). A similar city pair to the route (2) in the Berkeley model could be Trondheim-Bodø, but the author decided to select Trondheim-Bergen because of the relevance of aviation in that specific route, with no trains in between (mainly buses), a point that forces train travellers to travel all the way down to Oslo and then travel to Bergen (or vice versa), or via car. A similar city pair to route (3) is Bodø-Leknes, due to its location in the Lofoten islands, which are well known for their scenery, and due to Leknes being the biggest city in the islands as well as the Leknes airport having the largest passenger volume among the islands' airport (Avinor, 2020). As noted earlier, three types of planes were analysed in the Berkeley model and following company dialogue with Avinor in June 2020, were the aircraft providers Pipistrel and Heart Aerospace were mentioned, also mentioned in the study conducted by Alvestad et al. (2020), the author considers including these two aircraft to this study as a further avenue of research.

This study's aim is to move from the research problem to empirical observation (Olsen, 2020). One could argue that usually a case study that tries to develop a theory or a conclusion through observations is usually associated with an inductive approach (Olsen, 2020; Saunders et al., 2016). Indeed, the inductive method takes data from empiricism (i.e. current available technologies) to draw a general conclusion to a problem (Tranøy, 2017). However, for this study one could also argue for a deductive approach, because data is used to test a theory that already exists (Saunders et al., 2006). Indeed, the Berkeley model has already been set up and this study attempts to apply it to the Norwegian context to see if similar conclusions to the California case study can be derived in the Norwegian case. In addition, Alvestad et al. (2020) have been studying the Bergen-Stavanger route from a technical point of view. The research is designed building on the Berkeley model, the AERO model and the research by Alvestad et al. (2020), which supports the deductive approach. A policy-sensitive reproduction of the Berkeley model for the Norwegian context, with various routes and technologies and including a cost model, has not yet been conducted to the author‘s knowledge, hence the deductive model can again be argued for, because of the need for a literature review of reports as well as for attending conferences to understand the Norwegian context, on the policy and cost fronts (e.g. Norwegian airlines' fleet breakdown of operating costs per hour of flight). According to Alvestad et al. (2020), one could also argue for the deductive approach since the reality of this case originates from a rather unexplored field and little has yet been done to apply the technologies to the commercial industry. For example, the first ZeroAvia flight in a commercial setting was as recent as the 24th of September 2020. Therefore, the study concludes its approach section by arguing for an abductive approach, because data collection is used to explore observations, identify concepts and patterns, and to conceptualise these in a framework as well as to test through further data collection (Saunders et al., 2016). In an abductive approach, one usually moves back and forth from theory to data and vice versa. The fact that this thesis is strongly interdisciplinary also adds weight to finally chosen option of the abductive approach. When it comes to how theory is handled, the abductive approach attempts to modify existing theory or build new conclusions from what is existing (Saunders et al., 2016). Since the study reproduces the Berkeley model, taking an existing theory, but modifying it to apply to the Norwegian context, analysing and coming up with similar but new questions that the author wants to explore, hence moving from theory to data and data to theory, the author believes an abductive approach best suits the study's research design.

3.1.2. Data Type and Time Horizon

The study aims to use cross-sectional data as its purpose is to investigate the emission amount of the different types of aircrafts as compared to using the transport mode traditional aviation, via selected routes at a single point in time, and not how the emission levels can change over time. Longitudinal studies could be considered as an avenue of further research, where further contributors can choose to observe the hydrogen, battery or hybrid plane over a few years and observe emission and cost levels' changes. Due to improvements in technology, it is foreseen that cost levels will decrease, hence this is definitely an interesting avenue for further research. Finally, in mixed methods research, quantitative and qualitative techniques are combined in a variety of ways that range from simple, concurrent forms to more complex and sequential forms (Saunders et al., 2016).

3.1.3. Data collection

The study uses a combination of both primary and secondary data. Primary data was collected from company dialogues with Avinor as well as aircraft and technical solutions providers. Because the study is both an exploratory and an evaluative one, the author made use of semi-structured and unstructured interviews. The author expected the majority of the interviews to be semi-structured and unstructured based on the exploratory aspect and this means that coming up with all questions to ask beforehand is not preferred, rather, it is more suitable to keep in mind the theme or particular research area and form starter questions with the view to build on the answer by the interviewee. A few examples of questions asked to Avinor were: What routes do you see the most potential in focusing on? What do you think is relevant for the research considering the technologies and aircraft solutions that you have been analysing so far? With regards to policies, the author wished to know from both Avinor as well as aircraft manufacturers what kind of policies can incentivise airlines to adopt more cost-effective solutions, so a further question was: How are current policies helping you now and what can be improved? Secondary data was collected as mentioned through conferences as well from the cost model and economic model files provided by the Berkeley students. Further, this paper was written with availability of ZeroAvia's supervision, and thus, the author was given access to the necessary data through them. The technical data on the other studied aircraft was secondary data because it was obtained through company dialogues with Faradair and Eviation's Alice with the contributors to the Berkeley model. This kind of data is called secondary data, as it was initially collected for another purpose (Saunders et al., 2016). Finally, the author also made use of valuable secondary data on technologies, policies and passenger volumes for the models from reports, especially from the most recent of the reports on "Bærekraftig og samfunnsnyttig luftfart" (Avinor et al., October 2020).

3.2. Hypotheses and Model

The High-level Emission and Cost Reduction for Aviation (HECRA) Model includes the following subsystems and model: Technology, Environment, Economy and Policy. The Technology subsystem comprises the Characteristics Model. Environment subsystem includes: (1) a GHGs Emission Intensity Model and (2) a Route-Specific Emission Model. The Economy subsystem encompasses the Cost Model and finally the Policy subsystem encompasses the Incentive Model.

Following company dialogue with Avinor (2020), the routes chosen for the Route Selection section (1) Trondheim-Bergen, (2) Bergen-Stavanger and (3) Bodø-Leknes. The emission model gathers so-called emission factors per mode of transportation: traditional aviation versus hydrogen-electric, hybrid-electric and battery-electric aircraft. The latter are named "more cost and emission effective aviation solutions". Based on the model and literature review, the following are the study's hypotheses:

H1a: Based on modelled number of passengers and the technical data from company dialogues with Berkeley contributors, the ZeroAvia renewably–powered hydrogen–electric 19-seater HyFlyer is more emission-effective than the battery-electric based on modelled number of passengers and assumptions of hydrogen production from electrolysis in 2025 and more emission-effective than the hybrid-electric aircraft with on-site or nearby electrolysis plant.

H1b: Based on modelled number of passengers and the technical data from company dialogues with Berkeley contributors, the ZeroAvia renewably–powered hydrogen–electric 19-seater HyFlyer is more cost-competitive than the hybrid, the battery-electric aircraft and many of the traditional aircraft currently in use on the selected three reference routes. The renewably–powered hydrogen–electric aircraft is more emission-effective than the battery-electric based on modelled number of passengers and assumptions of hydrogen production from electrolysis in 2025 and more emission-effective than the hybrid-electric aircraft with on-site or nearby electrolysis plant.

H2: Some of the analysed aircraft compete well on some of the selected routes, particularly small routes, offering an economical alternative to current modes both in terms of time, money and availability of alternatives in the route.

H3: Policy initiatives can make the studied aircraft solutions more cost competitive.

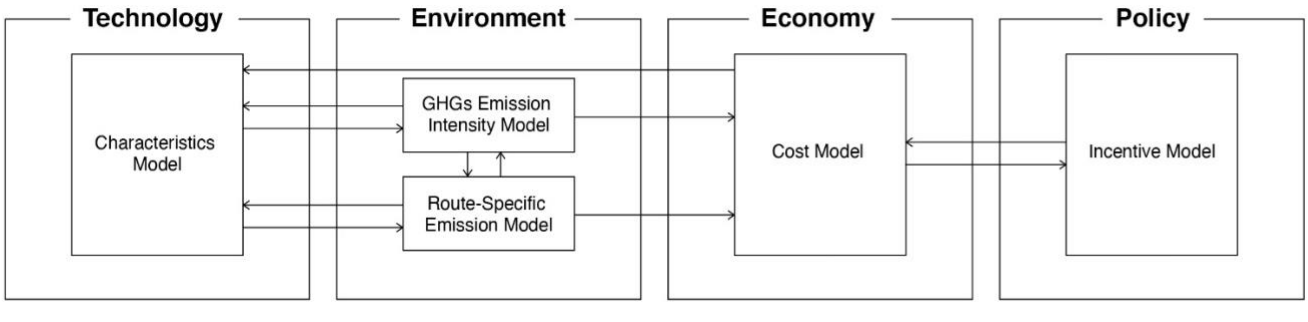


Figure 14. High-level Emission and Cost Reduction for Aviation (HECRA) Model Representation

Figure 15. Availability of alternatives to aviation on the selected routes from Avinor (2017)

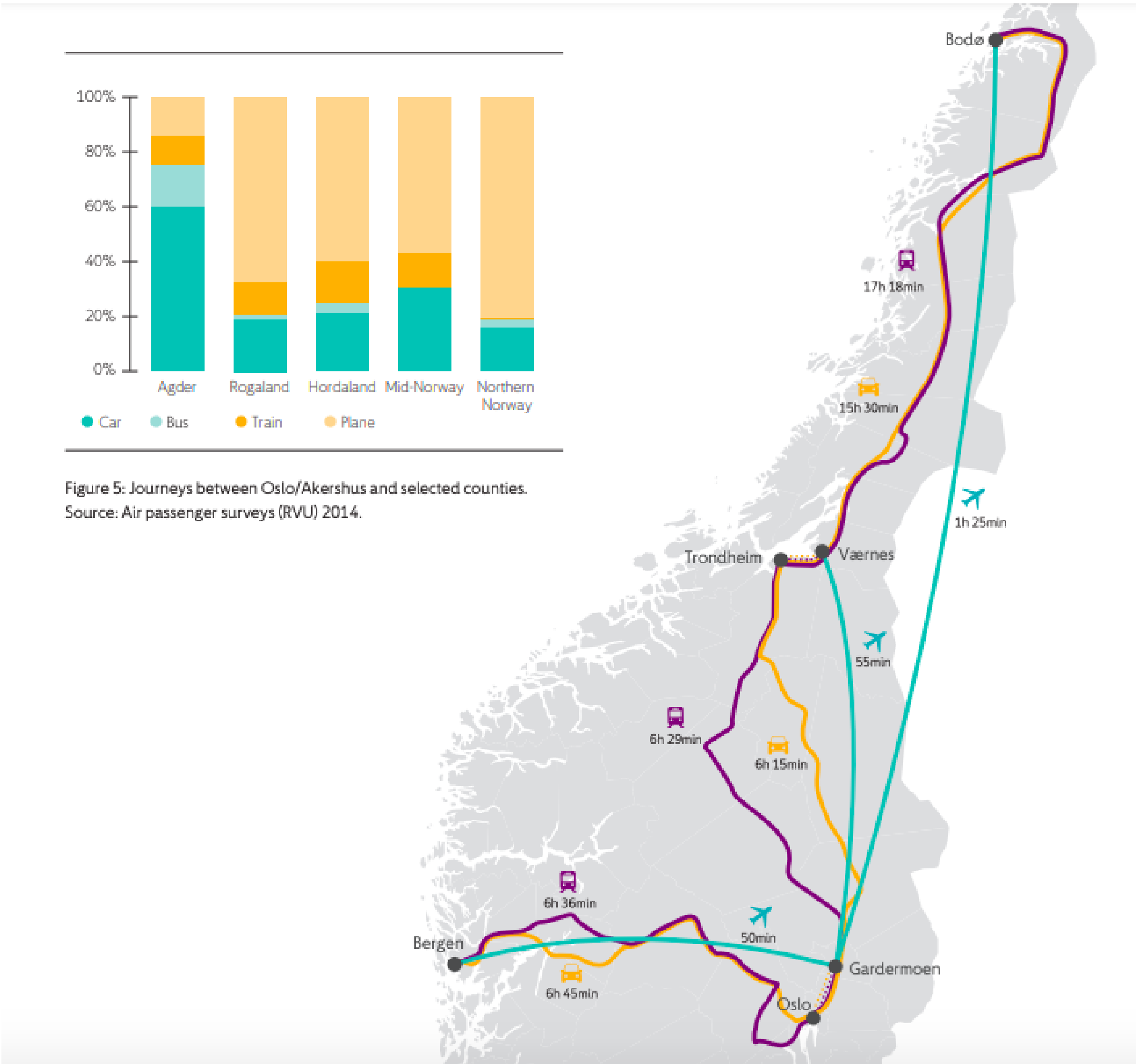


Figure 16. Availability of alternatives to aviation on the selected routes from Avinor (October 2020)

4. High-level Emission and Cost Reduction for Aviation (HECRA) Model, Data and Assumptions

4.1. Technology: Characteristics Model

As the literature review highlighted, “technology is by far the most important overall factor for cutting GHGs emissions, embracing both aircraft and engine technology and sustainable aviation fuels (SAFs)” (CAPA – Centre for Aviation, 2021). Indeed, as can be seen in the model representation in chapter 3, all the following models are based on engine and aircraft technology innovation, hence on the assumptions and calculations made in the Technology subsystem. The main aircraft characteristics in the Characteristics Model represent secondary data obtained through the Berkeley Model’s bibliography as well as company dialogues between ZeroAvia, Faradair and Eviation’s Alice and the contributors to the Berkeley model. In addition to having more than one researcher replicating the data analysis (Berkeley model, 2020, with a similar model structure and similar route characteristics; Alvestad et al., 2020, with one of the same routes – Bergen-Stavanger), the author was able to obtain cross-check of the Characteristics Model by more than one employee, at least in relation to ZeroAvia’s characteristics as well as ZeroAvia’s assumptions. This is known as inter-rater reliability. All in all, these characteristics have been proofread by at least 5 contributors, from the Berkeley model contributors, to the Master thesis author and the ZeroAvia trainee internally.

Fundamental to read the Characteristics Model is the color code. Displayed in red are the assumptions that were originally made by the Berkeley model contributors when building the Berkeley model’s Characteristics Model. Displayed in green are the cross-checking inputs from the internal dialogue within ZeroAvia.

Table 2 shows the main aircraft characteristics. From the Berkeley model the author knows that the cruise fuel economy for the hydrogen-electric plane was calculated from ZeroAvia’s provided data as follows: a 300 nautical miles flight consumed 60 kg hydrogen (H2). In addition, one third of fuel (20kg) was used for take off, hence the 6-seater has a cruise fuel economy of 7.5 mi/kg. From ZeroAvia’s internal review the author knows that ZeroAvia is currently modeling 19-seater on Dornier 22, with cruise speeds closer to 413 km/hr.

Table 2. Characteristics Model

Hydrogen-electric, hybrid-electric and battery-electric

	Type of airplane	ZeroAvia		BEHA M1_H	Alice
	Development phase	Test	Development	Development	Test
	Type of fuel	Compressed hydrogen		Electricity & SAF	Electricity
	Number of passengers	6	19	18	9
Taxi in + out + idle	Power (kW)	18.2	**60**	35	63
LTO	Runway length (m)	200	?	300	914
	LTO power (kW)	260	**600**	500	900
	LTO fuel requirement (kg or kWh)	20	33	0	21
Cruise	Range (nm)	260.64	434.40	1000+	540
	Range (miles)	300	500	1151	621.54
	Reserve (min/miles)		-	-	45 / 25
	Cruise speed (km/h)	280	**413 (a)**	370	444.48
	Cruise power (kW)	85	255	N/A	260
	Cruise fuel economy (mi/kg) **(b)**	7.5	7.46	0.789310131	
	Cruise fuel economy (kg/h)		**41.6 KG/hr**	0	N/A
Mass	Payload (t)	-	-	5	-
	Useful load	-	-	-	1,134
	MTOW	2,000	-	-	6,350
	Empty weight	-	-	-	
	Battery weight (kg)	2*50	-	-	3,600
Battery	Energy density (Wh/kg)	-	-	-	-
	Specific power (W/kg)	-	-	-	-
	Max power (kW)	260	**600**	500	900
	Energy (kWh)	-	-	-	920
Motor	Number of electric motor	2	More than 2	1	3
	Peak power (kW)	260	**600**	500	900
	Solar panels	No	No	Yes	No
	Size of fuel tank (kg)	60	100	-	-
	Turboprop (hp)	-	-	1,600	-
Noise	Noise (dBa)	60	60	60	N/A

4.2. Environment: Greenhouse Gas Emission Intensity Model

4.2.1. GHGs Emission Intensity Model – California

The building of the Emission Model for the California's model followed a life-cycle assessment study of various energy carriers, as shown in Table 3. This table and its assumptions were studied in order to build the GHG Emission Intensity Model for Norway. The life-cycle assessment study of various energy carriers is linked at source 1 of Table 3 and was provided by the Berkeley model contributors through University and company dialogues.

Table 3: GHG Emission Intensity Model - Berkeley Model, California

Fuel type	Type	Kg CO2-eq per kWh	Kg CO2-eq per kg fuel	Kg CO2-eq per L	Source
Hydrogen 2019	Compressed	10.938	10.500		[1]
Hydrogen in 2025	Compressed	2.200	4.400		[1]
Jet A Tailpipe			3.181	2.558	[2]
Jet A Well to tank			1.351	1.086	[1]
Jet A Sum			4.533	3.644	[1,2]
SAF			0.907	0.729	[3]
Electricity mix	CA average	0.197			[4]

[1] Datta, R., Osseiran, L., Bernard, M. R., and Romo, J. (2019). "Environmental Impact and Cost Comparison of Hydrogen- and Battery-Electric Light Aircraft for Regional Flights." CE / ER 290: Alternative Transportation Fuels and Technology. University and company dialogues with Berkeley model contributors.

[2] Rahman, M. M., Canter, C., & Kumar, A. (2015). Well-to-wheel life cycle assessment of transportation fuels derived from different North American conventional crudes. Applied Energy, 156, 159-173. Retrieved May 2020 from https://doi.org/10.1016/j.apenergy.2015.07.004.

[3] SAF assumptions at the SFO airport, California: https://www.flysfo.com/environment/sustainable-aviation-fuel.

[4] California's electricity mix: https://www.eia.gov/electricity/state/california/

Hydrogen California 2019

Based on the full jet fuel and hydrogen life cycle assessment conducted for California, Datta et al. (2019) assert that the carbon footprint of compressed hydrogen was 10.5 kg of CO2-eq per kg of H2 fuel, as of 2019.

Following are the main formulas used for the calculation of hydrogen's environmental footprint. The Californian hydrogen's environmental footprint is subdivided into these three main sources: (1) hydrogen production, (2) hydrogen transport and (3) hydrogen physical transformation.

The first formula is used for the estimation of hydrogen's environmental footprint during production:

1. GHG Production H2 =

SUM of % from source * source LCA emissions (in g CO2-eq/kg H2).

The second formula is used for the estimation of hydrogen's environmental footprint during transportation from the production source to the airport:

2. GHG Transport H2 =

Distance * LCA figure (truck type) * usual truck payloadload of H2 transported.

Since hydrogen requires physical transformation before being transported – it is either compressed or liquified – and these processes require energy, this third formula is used for the estimation of hydrogen's environmental footprint during hydrogen's transformation before transportation:

GHG Transformation H2 =

Energy consumed in kW * GHG of the grid * g CO2-eqkW.

The breakdown of the well-to-tank (WTT) GHG emissions for hydrogen in California is as follows, according to Datta et al. (2019):

To	San Francisco	Los Angeles
Form of Hydrogen	Liquified	Compressed
Production (kg CO2 eq/kg H2)	7.8	7.8
Transport (kg CO2 eq/kg H2)	3.0	1.4
Physical transformation (kg CO2 eq/kg H2)	1.7	1.3
GHG emissions (kgCO2e/kg H2)	***12.5***	***10.5***

Figure 17. Well-To-Tank (WTT) GHG Emissions for Hydrogen in California

Hydrogen California 2025

According to Datta et al. (2019) and Schefter et al. (2019), the benchmark hydrogen GHG intensity for comparison with traditional aviation, hybrid-electric and fully electric is based on 2025 numbers, since realistically flights of the planes that are undergoing design, modelling and certification in this first half of the decade could take place from around 2025.

The authors Datta et al. (2019) forecast, under the assumption that the technology remains the same (with no increase of the fuel economy, which might not be likely to happen), that the environmental impact of hydrogen would decrease by half by 2025, based on two renewable hydrogen plant projects planned in 2018 (Cazel, 2018) and that according to Schefter et al. (2019) are likely to operate in 2025. The two renewable hydrogen plants are going to be located in Bay Point, CA – less than 200 miles distant from San Francisco's (SFO) airport and Sacramento's airport (two of the key airports in the Californian model's studied routes) – and in Moreno Valley, CA – also less than 200 miles distant from Los Angeles. According to Datta et al. (2019): "The plants being more accessible from the airports means that hydrogen could always be transported as compressed". Concerning the physical transformation, the authors forecast reduced GHG emissions based on the strong Californian government's policies undertaken to make California's grid heavily reliant on renewables (California State Portal, 2018). Especially relevant under the latest Californian environmental policies is 2018 Senate Bill (SB) 100, signed by Governor Brown, and establishing that the Californian electricity system should: be powered from renewable energy resources by at least 50 percent by 2025 and 60 percent by 2030, and lead to the implementation of a zero-carbon electricity grid by 2045. In addition, "the Governor issued an executive order directing the state to achieve carbon neutrality by 2045" (California State Portal, 2018). With the sum of the policies, according to Governor Brown, "California establishes the most ambitious carbon neutrality commitment of any major economic jurisdiction in the world – of more than 20 countries and at least 40 cities, states and provinces planning to go carbon neutral by mid-century or sooner" (California State Portal, 2018). Given especially SB100 and the following mentioned Californian executive order, Datta et al. (2019) forecast a rise in solar and wind, while predicting a decrease in coal and oil first, and a reduced GHG intensity of 4.4 kg CO2-eq per kg of hydrogen in 2025.

Jet A Fuel Tailpipe and Jet A Fuel Well-To-Tank (WTT)

For jet fuel, dwelling on Marie Rajon Bernard and Line Osseiran 2019 work, the well-to-tank emissions are 8.22 kg of CO2-eq per gallon of jet-fuel and the tailpipe/combustion emissions are 9.68 kg of CO2-eq per gallon of fuel (Rahman et al., 2015). The Berkeley model contributors thus obtained a total of 17.90 kg of CO2-eq per gallon of jet-fuel. According to information from the SFO airport website (SFO), SAFs cuts the life cycle emissions by 80%. Therefore, the Berkeley model contributors multiplied the value found for jet-fuel by 0.2 and obtained a carbon footprint of 3.58 kg of CO2 per gallon of SAF. Tailpipe emissions were also taken from the graph within Rahman et al. (2015) at around 73 grams/CO2-eq/MJ-jet fuel.

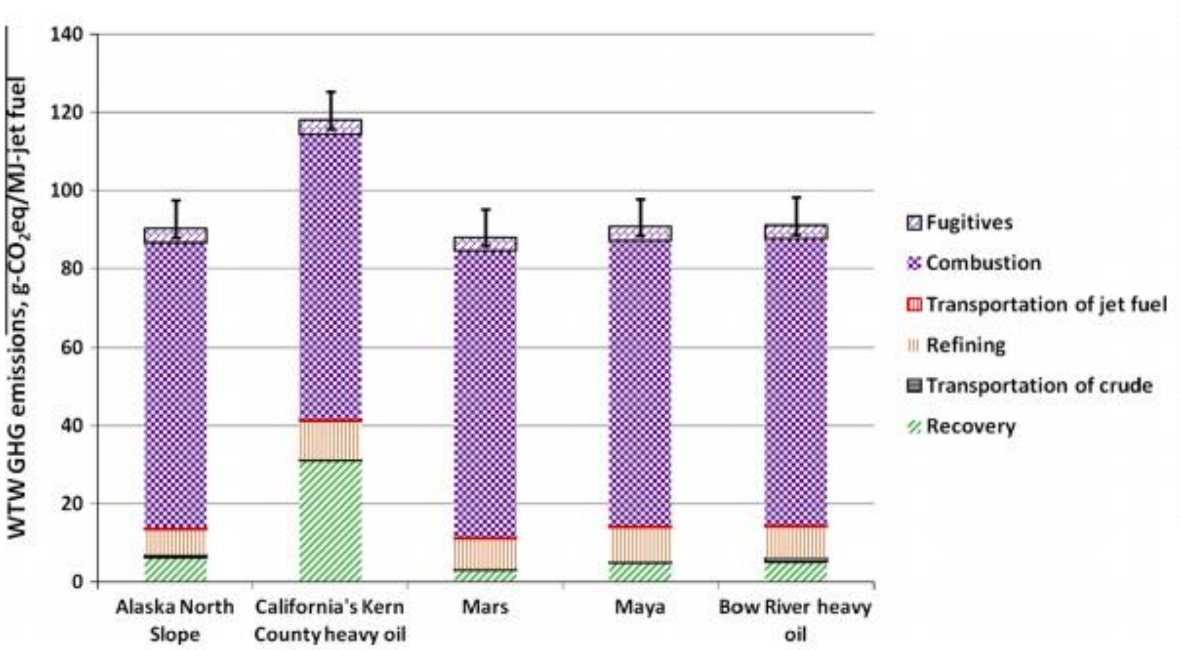


Figure 18. Life cycle WTW GHG emissions for diesel

Electricity

Concerning electricity, California is decreasing the carbon intensity of its electricity grid. The Berkeley model contributors took an average of the carbon intensity of the Californian grid in 2018: 0.223 kg of CO2eq per kWh according to the U.S. EIA (Energy Information Administration) (EIA 2019) and then took the goal of 0.178 kg of CO2eq per kWh by 2030 (Robbie Orvis, 2015) and assumed a linear decrease in the carbon intensity to obtain the carbon intensity of 2025, which is 0.20 kg of CO2eq per kWh.

4.2.2. GHGs Emission Intensity Model – Norway

Table 4: GHG Emission Intensity Model - NHH Model, Norway

Fuel type	Kg CO2-eq per kWh	Kg CO2-eq per kg fuel	Kg CO2-eq per L	Source
Hydrogen from Norwegian hydro directly, 2021	0.208	0.200		[5, 6, 7, 15, 16]
Hydrogen 2025	2.100	**4.200**		[5, 6, 7, 15, 16]
H2 from water electrolysis 2025, solar energy	1.200	2.400		[5, 6, 7, 15, 16]
H2 from water electrolysis 2025, wind energy	0.485	0.970		[5, 6, 7, 15, 16]
Jet A Avinor		3.874	3.115	[8, 9, 10]
SAF		0.775	0.623	[10,11]
Electricity mix	0.240			[12,13,14]

[5]	Sternberg, A., Hank, C., & Hebling, C. (2019). Greenhouse Gas Emissions for Battery Electric and Fuel Cell Electric Vehicles with Ranges over 300 kilometers: Study Commissioned by H 2 Mobility. Fraunhofer.
[6]	SINTEF (2020). Largescale hydrogen production in Norway - possible transition pathways towards 2050. Link.
[7]	DNV GL (2019). Produksjon og bruk av hydrogen i Norge. Link.
[8]	ICAO. Aviation Climate Policy & Lower Carbon Aviation Fuel. Jean-Christophe Monfort. Saudi Arabia. Link.
[9]	European Environment Agency CORINAIR manual (2001). Link.
[10]	Wormslev, E. C. (2016). Sustainable jet fuel for aviation: Nordic perpectives on the use of advanced sustainable jet fuel for aviation. Nordic Council of Ministers. Page 201. Link.
[11]	SAF assumptions at the SFO airport, California: Link.
[12]	Energifakta Norge. Link.
[13]	NVE (2017). Electricity Disclosure. Link.
[14]	Valente, A., Iribarren, D., & Dufour, J. (2017). Harmonised life-cycle global warming impact of renewable hydrogen. Journal of Cleaner Production, 149, 762-772.
[15]	Datta, R., Osseiran, L., Bernard, M. R., and Romo, J. (2019). "Environmental Impact and Cost Comparison of Hydrogen- and Battery-Electric Light Aircraft for Regional Flights." CE / ER 290: Alternative Transportation Fuels and Technology. University and company dialogues with Berkeley model contributors.
[16]	Fuel cells works (2021). Nel and Statkraft to develop a green hydrogen project. Link.
[17]	Norwegian Hydrogen National Strategy. Link.

Hydrogen Norway

On hydrogen lyfe-cycle assessment for Norway, numbers on water electrolysis from solar energy and wind energy were taken from Datta et al. (2019), since they were found to be in line with various other studies, such as the study by Ozbilen et al. (2013), presented in Figure 20.

Figures 19 and 20 present global warming potential (GWP) values for various methods of hydrogen production, with GWP used in this study interchangeably with the term GHG intensity, from Datta et al. (2019).

Hydrogen Production Method	GWP values (kg CO2eq/kg H2)
Steam reforming of natural gas	11.9
Coal gasification	11.3
Water electrolysis via wind energy	0.970
Water electrolysis via solar energy	2.41

Figure 19. GWP values per method of hydrogen production, from Datta et al. (2019)

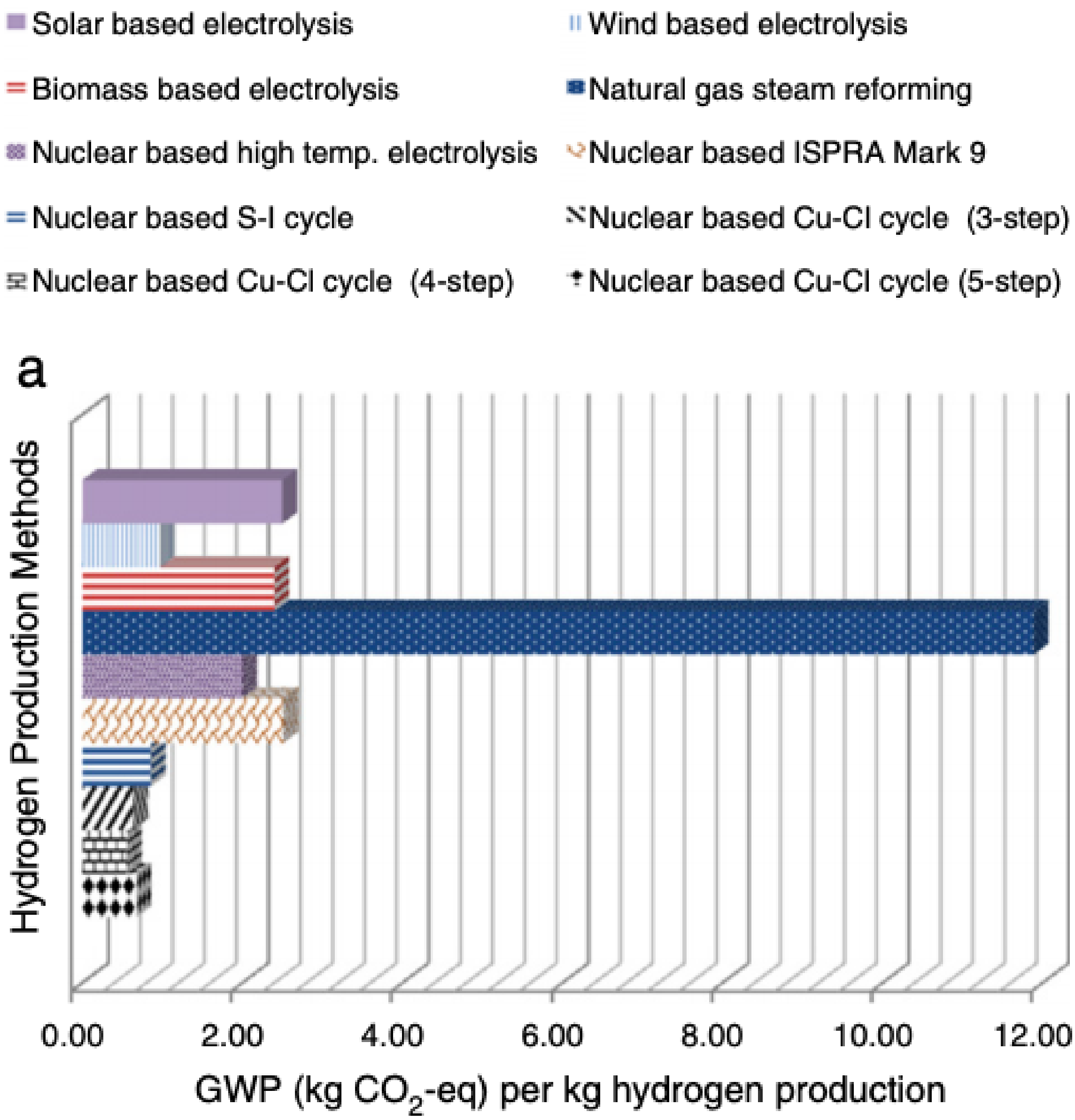


Figure 20. GWP values per method of hydrogen production, from Ozbilen et al. (2013)

For hydrogen in 2025-2030, according to Damman et al. (2020), source [6], a demand of 1/3 of used hydrogen for transportation to be produced from electrolysis was exogenously added to the model analyses, since it was not considered realistic that all parts of Norway could have access to hydrogen from SMR at the price assumed.

In addition, Motazedi et al. (2021) assert that water electrolysis powered by a low carbon electricity source may be a promising alternative option for hydrogen production with relatively low life cycle GHG emissions (a range of 1-5 kg CO_2e per kg H_2 has been reported in the literature), therefore 4.2 Kg CO_2-eq per kg H_2 fuel are considered as the assumption for this study for Norway. This is considering the total production share with electrolysis that could happen by 2025-2030. However, the model also includes the assumption that hydrogen could be produced by an on-site or nearby plant, whereby the hydrogen's environmental impact could be up to 0.8 if coupled with electrolysis with wind energy, according to company dialogue with ZeroAvia.

In fact, according to Ghandehariun and Kumar (2016): "The total GHG emissions of a wind-based hydrogen production plant are estimated to be 0.68 ± 0.05 kg CO_2 eq./kg H_2, 65% of which are from the construction of the wind power system. The results are compared with those of conventional fossil fuel-based systems. The overall GHG emissions from wind-based hydrogen production are about 94% lower than those associated with hydrogen production through steam methane reforming (SMR). Natural gas-based hydrogen production emissions are mainly found in the plant operation stage. For wind-to-hydrogen systems, the manufacturing and installation of the systems have significant environmental impacts. However, the hydrogen produced from wind energy can significantly reduce the GHG footprint of the energy industry".

Jet A Avinor, SAF and electricity for Norway

Life-cycle assessment data for jet fuel was obtained from the baseline life cycle emissions value for jet fuel, equal to 89 gCO_2e/MJ, found in source [8]. When it comes to SAF, the same assumption on 80% impact reduction as for the Berkeley model was taken. The formula to obtain kg CO_2-eq per kg fuel is the division of the kg CO_2-eq per liter by the energy density factor 0.804. For the electricity factor, 0.24 was taken from Energifakta Norge as from source [12].

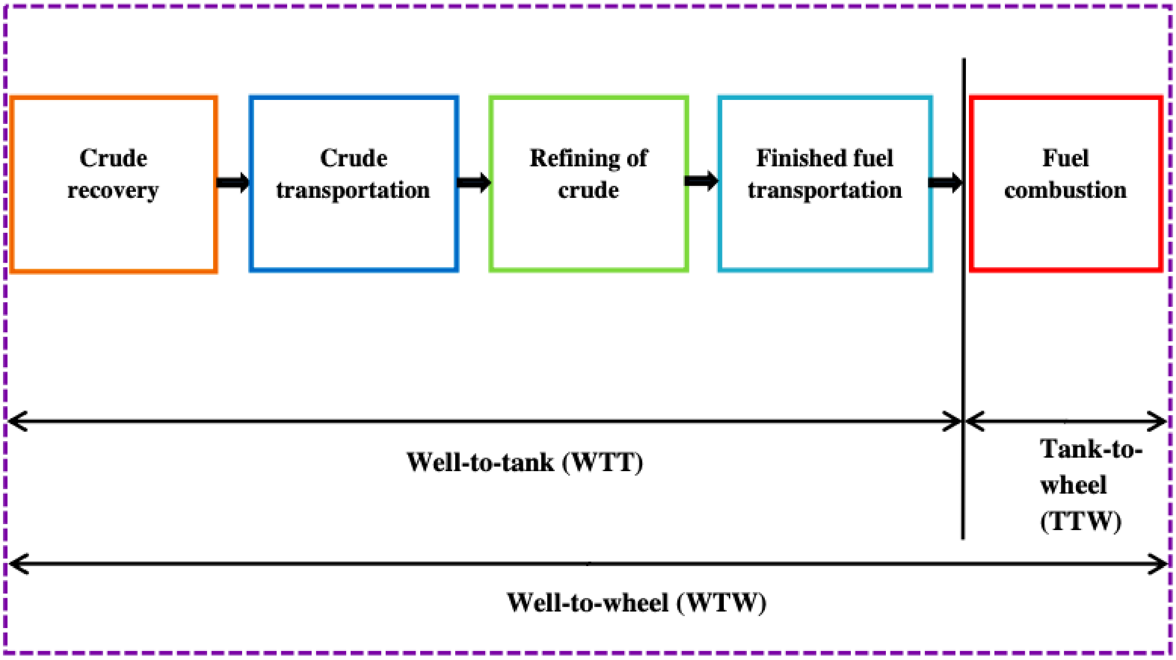


Figure 21. Jet A life-cycle assessment

4.3. Environment: Norwegian Route-specific Emission Model

For the Norwegian Route-specific Emission Model, data was collected from two sources: the ICAO's Emission Calculator and Airmilescalculator. Data needed to be collected as regards the total kilometers, total miles and nautical miles as well as total travel time in minutes, per selected route. Six minutes is estimated to be an average landing and take-off (LTO) time by ICAO and Eurocontrol. Data is displayed in Table 5-1.

Table 5-1: Norwegian Route-specific Emission Model – NHH Model, Norway

Airplane Mission			
	Route 1	Route 2	Route 3
	Trondheim - Bergen	Bergen - Stavanger	Bodø - Leknes
Estimated flight time (min)	62	41	37
Total distance (mi)	288	99	64
Total distance (km)	463	160	104
Total distance (nm)	250	86	56
LTO (time in min)	6	6	6
Load Factor	1	1	1

Table 5-2: Norwegian Route-specific Emission Model – NHH Model, Norway

Traditional aviation's emissions				
	Route 2	Route 1	Route 3	Sources
	Bergen - Stavanger	Trondheim - Bergen	Bodø - Leknes	
Total distance (miles)	99	288	64	Airmiles [18]
Total distance (km)	160	463	104	Airmiles
Tot distance (nm)	86	250	56	Airmiles
Kg of CO2 emissions per passenger	**40**	**67**	**34**	**Airmiles**
	31	**64**	**26**	**ICAO [19]**
Estimated flight time (min)	41	62	37	Airmiles

Table 5-3: Norwegian Route-specific Emission Model – NHH Model, Norway

ZeroAvia (2025 assumptions)			
	Route 1	Route 2	Route 3
Taxi-in + out + gate (time in min)	20.00	20.00	20.00
Taxi-in + out + gate (kW)	60.00	60.00	60.00
Taxi-in + out + gate (kWh)	20.00	20.00	20.00
Taxi-in + out + gate (emissions kg of CO2)	42.00	42.00	42.00
LTO (kWh)			
LTO (kg of fuel)	30.00	30.00	30.00
LTO (emissions in kg of CO2)	126.00	126.00	126.00
Cruise (kWh)	421.66	145.71	94.71
Cruise time (hr)	1.65	0.57	0.37
Cruise (kg of fuel)	38.59	13.27	8.58
Cruise (emissions kg of CO2)	162.09	55.72	36.02
Total emissions (kg of CO2)	330.09	223.72	204.02
Total emissions per pax (kg of CO2/pax)	17.37	11.77	10.74

The second step was then to collect the traditional aviation emissions from the two sources mentioned (ICAO and Airmilescalculator), to compare with the three new aircraft technologies studied.

The third step was to calculate ZeroAvia's emissions on the three routes, the fourth step to calculate Faraidair's emissions and the fifth step to calculate Alice's emissions. The formulas, which can be found in the Excel Appendix, were given from the Berkeley's model. Finally, step six was to compare aircraft emissions.

Table 5-4: Norwegian Route-specific Emission Model – NHH Model, Norway

BEHA M1_H			
	Route 1	Route 2	Route 3
Taxi-in + out + gate (time in min)	20.00	20.00	20.00
Taxi-in + out + gate (kW)	35.00	35.00	35.00
Taxi-in + out + gate (kWh)	11.67	11.67	11.67
Taxi-in + out + gate (emissions kg of CO2)	2.80	2.80	2.80
LTO (MJ)	0.00	0.00	0.00
LTO (kg of fuel)	0.00	0.00	0.00
LTO (emissions in kg of CO2)	0.00	0.00	0.00
Cruise			
Cruise time (hr)	1.25	0.43	0.28
Cruise (kg)	364.88	125.43	81.08
Cruise (emissions kg of CO2)	282.73	97.19	62.83
Total emissions (kg of CO2)	285.53	99.99	65.63
Total emissions per passengers (kg of CO2/pax)	15.86	5.55	3.65

Table 5-5: Norwegian Route-specific Emission Model – NHH Model, Norway

Alice			
	Route 1	Route 2	Route 3
Taxi-in + out + gate (time in min)	20.00	20.00	20.00
Taxi-in + out + gate (kW)	63.00	63.00	63.00
Taxi-in + out + gate (kWh)	21.00	21.00	21.00
Taxi-in + out + gate (emissions kg of CO2)	5.04	5.04	5.04
LTO (kWh)	90.00	90.00	90.00
LTO (emissions in kg of CO2)	21.60	21.60	21.60
Cruise (kWh)	270.83	93.59	60.84
Cruise time (hr)	1.04	0.36	0.23
Cruise (kg of fuel)			
Cruise (emissions in kg of CO2)	65.00	22.46	14.60
Total emissions (kg of CO2)	91.64	49.10	41.24
Total emissions per passengers (kg of CO2/pax)	10.18	5.46	4.58

Table 5-6: Norwegian Route-specific Emission Model – NHH Model, Norway

Route Emission Results Summary	Route 1	Route 2	Route 3
ZeroAvia	17.37	11.77	10.74
BEHA M1_H	15.86	5.55	3.65
Alice	10.18	5.46	4.58

4.4. Economy: Cost Model

Step one for setup of the Cost Model was to collect data on the airlines that currently offer service on the studied routes. This is 2021 data, so it definitely is a further avenue of research to look more into detail into the volumes of flights prior to 2020. This data collection on airlines was performed through Google Flights. Step two was to collect data on the total hourly cost (fixed and direct costs) per aircraft type. Sources per aircraft are displayed in the tables below. Step three was to also collect data on whether the aircraft are flying with or without stops, which increases flight time, hence fares.

Table 6: Cost Model, Route 1

Airlines	Route 1 Trondheim - Bergen	Total Hourly Cost (Fixed+Direct)	Connecting flights/stops
Widerøe	De Havilland DHC-8 400	$5,017.95	Currently up to 38% have stop in Oslo, Sandefjord or Tromsø (2021).
	De Havilland DHC-8 100	$4,035.15	
	Embraer 190 E2	$4,326.75	
SAS	Boeing 737-700	$8,241.36	Oslo
	Airbus A320neo	$7,007.22	
Norwegian	Boeing 737-800 (average costs taken)	$6,075.00	Oslo
KLM (Amsterdam transfer = at least 195 min)	Embraer 175	$3,712.30	Currently all flights have transfer in Amsterdam.

Table 7: Cost Model, Route 2

Airlines	Route 2 Bergen - Stavanger	Total Hourly Cost (Fixed and Direct)	Connecting flights/stops
Widerøe	De Havilland DHC-8 400	$5,017.95	Currently 25% have stop in Oslo (2021), where the 8 100 is used (for the stop in Oslo both routes 1 and 2).
	De Havilland DHC-8 100	$4,035.15	
	Embraer 190 E2	$4,326.75	
SAS	Boeing 737-700	$8,241.36	At least 70% of the flights per day have stops in Oslo or Trondheim (2021).
	Airbus A320neo	$7,007.22	
Norwegian	Boeing 737-800	$6,075.00	Currently >90% flights to 100% per day have stop in Oslo (2021).
KLM (Amsterdam transfer = at least 195 min)	Embraer 175	$3,712.30	Currently all flights have transfer in Amsterdam.

Table 8: Cost Model, Route 3

Airlines	Route 3 Bodø - Leknes	Total Hourly Cost (Fixed+Direct)	Connecting flights/stops	Sources
Widerøe	De Havilland-Bombardier Dash-8 100/200	$4,035.15	Leknes-Bodø always direct but transiting within Lofoten airports always with >= one stop (Bodø) and in some cases another airport.	[26, 30] [26, 31] [26, 32]
SAS	Flies with Widerøe Oslo-Leknes as above but more hours because not direct.	$4,035.15	Oslo	[27, 33] [27, 34]
Norwegian	-	-	-	[28, 35]
KLM (Amsterdam transfer = at least 195 min)	-	-	-	[29, 32]

Sources

[26] Wideroe.no

[27] SAS.se

[28] Norwegian.no

[29] KLM.nl

[30] Operating Costs 8-Q400

[31] Operating Costs Dash 8-100

[32] Operating Costs Embraer 190 and 175

[33] Operating Costs 737-700

[34] Operating Costs Airbus A320neo

[35] Operating Costs 737-800

E190-E2

Max operating speed: 890 km/h
Engines: Pratt & Whitney 1919G Geared turbofan
Wing span: 33,7 meter
Length: 36,3 meter
Number of seats: 110
Number of aircraft: 3

DASH-8 Q400

Max.cruise speed: 667 km/t
Max.take-off weight: 29.574 kg
Engines: 2 x 5.071 hk Pratt & Whitney PW150A turboprop
Wingspan: 28,42 m
Length: 32,8 m
Number of seats: 78
Number of aircraft: 10

DASH-8 300

Max.cruise speed: 501 km/t
Max.take-off weight: 19.500 kg
Engines: 2 x 2.380 hk Pratt & Whitney PW123 turboprop
Wingspan: 27,4 m
Length: 25,7 m
Number of seats: 50
Number of aircraft: 4

DASH-8 100 / Q200

Max.cruise speed: 482 km/h / 518 km/h
Max.take-off weight: 15.966 kg / 16.446 kg
Engines: 2 x 2.150 hk Pratt & Whitney PW121 / 2 x 2.262 hk PW 123D
Pratt & Whitney
Wingspan: 25,9 m
Length: 22,3 m
Number of seats: 39
Number of aircraft: 26

Figure 22: Widerøe’s fleet (Widerøe, 2021)

Operating costs are expressed with an average of 400 annual flight hours, based on the sources found.

All the sources found for total hourly costs of aircraft were based on American estimates and American airlines. Hence, the American estimates were multiplied by a factor of 1.35 due to around 35% difference in nominal wages between USA and Norway (2019) according to Global Wage Report, International Labor Organisation.

Step four was to add a 6.2% margin to the operating costs, based on CAPA – Centre for Aviation (2019). Step five was to divide the total operating costs including 6.2% margin by the number of passengers per aircraft.

Table 9: Cost Model, Fares

Airlines	Route 1	Total Hourly Cost (Fixed+Direct)	Route 1 in Hours + 6.2% margin	Route 2	Total Hourly Cost (Fixed and Direct)	Route 2 in Hours + 6.2% margin	Route 3	Total Hourly Cost (Fixed+Direct)	Route 1 Hours + 6.2% margin
	Trondheim - Bergen		1.03	Bergen - Stavanger		0.68	Bodø - Leknes		0.62
Widerøe	De Havilland DHC-8 400	$5,017.95	$5,496.33	De Havilland DHC-8 400	$5,017.95	$3,634.67	De Havilland DHC-8 100/200	$4,035.15	$2,637.64
	De Havilland DHC-8 100	$4,035.15	$4,419.83	De Havilland DHC-8 100	$4,035.15	$2,922.79			
	Embraer 190 E2	$4,326.75	$4,739.23	Embraer 190 E2	$4,326.75	$3,134.01			
SAS	Boeing 737-700	$8,241.36	$9,027.03	Boeing 737-700	$8,241.36	$5,969.49	-	-	
	Airbus A320neo	$7,007.22	$12,998.38	Airbus A320neo	$7,007.22	$12,998.38	-	-	
Norwegian	Boeing 737-800	$6,075.00	$11,269.13	Boeing 737-800	$6,075.00	$11,269.13	-	-	-
KLM	Embraer 175	$3,712.30	$12,788.87	Embraer 175	$3,712.30	$12,788.87	-	-	-
X	ZeroAvia	-	-	ZeroAvia	-	-	ZeroAvia	-	-
X	Eviation Alice	$1,193.97	$1,307.80	Eviation Alice	$1,193.97	$864.83	Eviation Alice	$1,193.97	$780.46
X	BEHA MH1	$3,272.38	$3,272.38	BEHA MH1	$3,272.38	$2,370.29	BEHA MH1	$3,272.38	$2,139.05

	Route 1	Passengers	Fares Route 1	Route 2	Passengers	Fares Route 2	Route 3	Passengers	Fares Route 2
	Trondheim - Bergen		1.03	Bergen - Stavanger		0.68	Bodø - Leknes		0.62
Fares per route	De Havilland DHC-8 400	78	$70.47	De Havilland DHC-8 400	78	$46.60	78	78	-
	De Havilland DHC-8 100	39	$113.33	De Havilland DHC-8 100	39	$74.94	39	39	$33.82
	Embraer 190 E2	106	$44.71	Embraer 190 E2	106	$29.57	106	106	-
	Boeing 737-700	126	$71.64	Boeing 737-700	126	$56.32	126	126	-
	Airbus A320neo	174	$74.70	Airbus A320neo	174	$74.70	174	174	-
	Boeing 737-800	162	$69.56	Boeing 737-800	162	$69.56	162	162	-
	Embraer 175	88	$145.33	Embraer 175	88	$145.33	88	88	-
	ZeroAvia	19	$55.56	ZeroAvia	19	$20.39	ZeroAvia	19	$13.25
	Eviation Alice	9	$145.31	Eviation Alice	9	$96.09	Eviation Alice	9	$86.72
	BEHA MH1	18	$181.80	BEHA MH1	18	$131.68	BEHA MH1	18	$118.84

The 1.35 factor assumption could be further strengthened by an extra analysis with an attempt to breakdown Widerøe's 2019 operating costs, which however might need further discerning of buildings costs.

Table 10: Cost Model, Further breakdown

	2019	
Widerøe operating costs aircraft and buildings	911,062,000	NOK

Widerøe flyflåte 2019	42	Airplanes
Average operating costs	21,691,952	NOK
/400 annual flight hours	54229.88	Avg operating cost/h in NOK
Conversion in $	6480.58	Avg operating cost/h in $

4.5. Policy: Incentive Model and Policy Recommendations

The following policies were identified especially from the last Avinor et al. (2020)'s report on Sustainable Aviation.

(1) Blending mandate for advanced jet biofuel: In 2020, the blending mandate is 0.5%, with a target in the National Transport Plan 2018-2029 of 30 per cent by 2030. The blending mandate's path to 30 per cent mixed biofuels by 2030 has not been defined. "The government's goal is that by 2030, 30% of airline fuel will be sustainable and with climate benefits. By establishing a blending requirement, we can ensure that there is a market for alternative aviation fuels. This will facilitate technology and industry development in Norway". Ola Elvestuen, Minister of Climate and the Environment 2018-2020.

(2) Air passenger duty: NOK 76.50 per passenger within Europe, NOK 204 per passenger outside Europe. The Ministry of Finance is clear that the air passenger duty is primarily a fiscal tax, but one that can have an effect of reducing emissions, as higher airfares can lead to lower demand.

(3) NOx tax: NOK 10.50 per kg of fuel. In 2008, a NOx fund was established where taxable enterprises can choose to be members. The fund's income finances emission reduction measures for members.

(4) Electricity for electrolysis exemption from consumer electricity tax: NOK 0.1613/kWh, 2020. Electricity supplied for use in electrolysis is currently exempt from the consumer tax on electricity.

(5) Tripling CO2 tax, from Climate Plan, January 2021: NOK 590/tonne, 2021 to 2000/tonne CO2 equivalents, 2030. The progressive increase of the cost of emitting CO2 gives stronger incentives to reduce emissions. The government will increase the flat CO2 tax by 5% every year for all sectors until 2025.

(6) EU ETS: EUR 50/tonne CO2 as of May 2021. Increasing prices for allowances provide stronger incentives for developing new technologies. From almost EUR 30/tonne in September 2020 to 50 EUR May 2021.

Policy Recommendations

The idea of environmental charging is a century old and there have been attempts to introduce such policy into aviation (Alamdari and Brewer, 1994). Fuel taxation, as a proxy for taxing carbon and other emissions, is perhaps the most widely discussed attempt to introduce policy into aviation. For example, the Swedish government imposed taxes in 1989 on domestic flights at a rate of 12 Swedish krona per km of nitrogen oxides and hydrocarbons, and 0.25 Swedish krona per km of carbon dioxide. In 1993, the CO2 tax was raised to 0.32 krona per km of carbon dioxide. The emission taxes were based on the average Linjeflyg (the main carrier at the time) emissions of a flight of 380 kms (Elofsson et al., 2018). “The optimum tax level that would encourage airlines to pursue such a policy would be very similar to that of the Swedish emissions tax imposed on domestic flights in 1989” (Alamdari and Brewer, 1994). “It is incredible that since the paper [Alamdari and Brewer, 1994] not much has changed” (Boeing company dialogue, 2021).

According to The Norwegian Government’s hydrogen strategy, conditions for hydrogen are ideal in Norway. Hence, the following are the policy recommendations based on the present study and building the Berkeley study:

(1) Within 2025, set ambitious timelines for zero-emission aircraft in aviation similar to Norwegian road vehicles policies, commensurate to zero-emission aircraft certifications happened by 2025. We know that by 2025, all new passenger cars, new light vans and new city buses will be zero-emission vehicles in Norway and that by 2030, all new heavier vans, 75 percent of new long-distance buses, and 50 percent of new trucks will be zero-emission. In addition, there are 14 different fiscal incentives in place bearing on vehicles, fuel or road use.

(2) Use PSO routes as a tool to reward the introduction of zero- or low-emission aircraft during the contract period. As Avinor mentions, prices for zero- or low-emission aircraft can indeed be cheaper due to lower environmental taxes.

(3) Fundamentally, add e-fuels, including hydrogen fuel cells, under the blending mandate for sustainable aviation fuels, and define path to 30% sustainable aviation fuels by 2030.

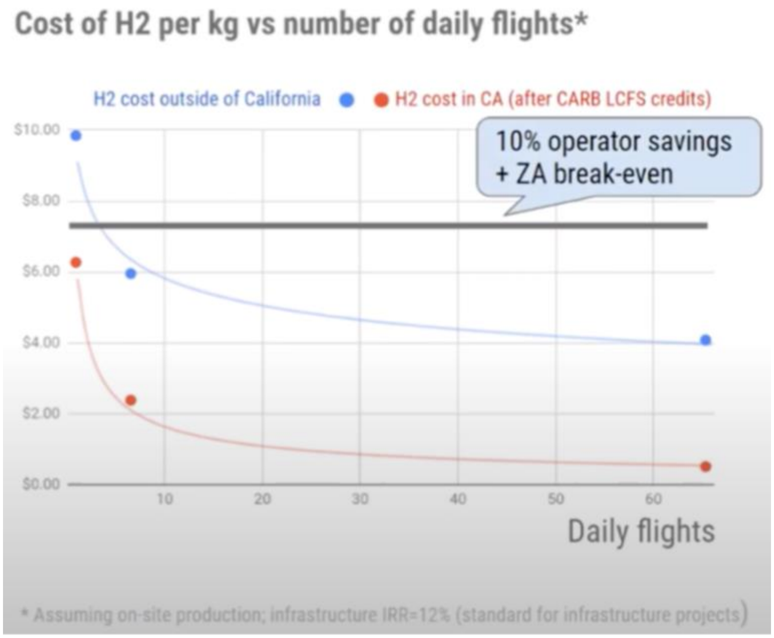


Figure 23: LCFS rebate

According to the Berkeley study, the difference between hydrogen fuel cost inside of California (red curve) and outside of California (blue curve) is about $3.8/kg, which comes from California's low-carbon fuel standards (LCFS) rebates. This diagram originates from calculations provided to ZeroAvia by their infrastructure partners.

This means that including hydrogen fuel cells under the blending mandate for sustainable aviation fuels could potentially make hydrogen-electric aircraft more cost-competitive than the entire fleet of aircraft flying on the studied routes.

(4) Consider proportionate landing fees to greenhouse gas emissions emitted during the landing and takeoff (LTO) cycle, based on recommendation also suggested by the Berkeley model contributors to California.

5. Analysis and Discussion

The author studied the formulas in the Berkeley model's emission model and cost model and applied them within the Norwegian case study. In the case in which it was hard to link formulas and references with each other, the author reached out to the Berkeley model's contributors.

Both a technical and environmental analysis were performed (Characteristics Model, GHGs Emission Intensity Model and Route-specific Emission Model) as well as a financial analysis (Cost Model). First, a route selection analysis is conducted, which is a qualitative analysis of the company dialogues and literature to explore motives for route selection. Following that, the step of the choice of aircraft and technologies for the model also stems from literature over the lists of projects and planned aircraft certification years (EASA, 2017; Posada, 2017). To set up the technical and environmental model and the financial model for Norway, first a quantitative data analysis of the data in the Berkeley Emission and Cost models was conducted. For the Emission model both this quantitative data analysis and the qualitative analysis of the fuel GHGs emission intensity information present in literature, i.e. Datta et al (2019) were performed. Then the author performed a quantitative data analysis of the collected data on the fleet of the airlines offering service for the studied routes, together with an analysis of the hourly cost per type of aircraft. Furthermore, an estimation was made on the number of flight hours per year in the Norwegian routes. Based on the Chapter 4 assumptions, fare costs per aircraft were calculated and a cost comparison across technology solutions conducted. On the policy front, the author analyzed existing policies through the four "Bærekraftig og samfunnsnyttig luftfart" reports and found correlations between certain policy initiatives and the potential to use incentives to increase the cost-competitiveness of adopting more cost- and emission-effective technology solutions.

As regards the technical and environmental analysis, it can be noted that the renewably-powered hydrogen-electric aircraft could be more emission-effective than the new aircraft technologies' colleagues when coupled with nearby electrolysis plant. In addition, the renewably-powered hydrogen-electric aircraft is already more emission-effective than the battery-electric due to 19-seater versus 9-seater modelled passengers. As regards the financial analysis, it can be observed that – based on verification of the assumptions – ZeroAvia's aircraft could already be more cost-competitive than 40 out of 43 aircraft in Widerøe's fleet.

6. Reliability and Validity

To ensure the quality of any research, an inquiry into the validity and reliability of tests and their subsequent results is required (Pedhazur and Schmelkin, 2013; Saunders et al., 2016). The author is concerned with internal and external reliability. Internal reliability is ensured by maintaining consistency throughout the research process and by establishing internal rules in the data collection and analysis process and ensuring adherence to the rules. Repeated exercises can be conducted when performing data analysis to ensure consistency. Using secondary data means little control over how the data was collected, which could lead to some problems. As such, the author carefully evaluated the data quality as well as suitability to the research before using the data. In terms of data analysis, more than one researcher has tried to replicate the results from data analysis (i.e. Berkeley model, 2020 & Alvestad et al., 2020), also known as inter-rater reliability. Several biases may be present that affect reliability when conducting semi-structured and structured interviews such as interviewer, response and participation bias. By creating a set of questions beforehand and having another fellow researcher review the questions, the author could strive to reduce interviewer bias. Response bias occurs when the respondent only gives a partial picture of the actual scenario, for example, the CEO of one aircraft manufacturing company might try to paint the company in a favorable light. Hence this bias can be mitigated by seeking to interview various employees within the organization (e.g. company dialogues with two ZeroAvia employees and a ZeroAvia intern). Participation bias can also be mitigated by taking care of the anonymity of interviewees and making sure they are comfortable with the setting of the interview. Further threats to reliability that can apply to this study can be errors that have been highlighted by the recent similar case study focused on the route Bergen-Stavanger (Alvestad et al., 2020), such as, among others, errors in calculation of drag and friction that could have happened, or in the calculation of the balance of the plane and fuel requirements affected by varying weather conditions.

Internal validity concerns whether we are measuring what we set out to measure (Saunders et al., 2016). Finding the environmental impact of the various aircraft options allows for comparison between the modes of transport and for understanding of which option can lead to less emissions. Since this research is conducted for a combination of exploratory and evaluative purposes, rather than establishing causal relationships, the author is not too concerned with causality, however internal validity is important in all studies. External validity refers to the possibility that this study will be able to be generalized across other settings. Further researchers can use the results from this study to draw conclusions on policy measures or to apply the findings to their own country contexts as the author did for the Norway case.

7. Conclusion

H1a and H1b are verified based on assumptions: Based on modelled number of passengers and the technical data from company dialogues with Berkeley contributors, the ZeroAvia renewably–powered hydrogen–electric 19-seater HyFlyer is more emission-effective than the battery-electric based on modelled number of passengers and assumptions of hydrogen production from electrolysis in 2025 and more emission-effective than the hybrid-electric aircraft with on-site or nearby electrolysis plant. Based on modelled number of passengers and the technical data from company dialogues with Berkeley contributors, the ZeroAvia renewably–powered hydrogen–electric 19-seater HyFlyer is more cost-competitive than the hybrid, the battery-electric aircraft and many of the traditional aircraft currently in use on the selected three reference routes. The renewably–powered hydrogen–electric aircraft is more emission-effective than the battery-electric based on modelled number of passengers and assumptions of hydrogen production from electrolysis in 2025 and more emission-effective than the hybrid-electric aircraft with on-site or nearby electrolysis plant.

H2 is verified based on assumptions: Through analysis of the financial model, we compare the cost per mile for each type of airplane when travelling over the study routes, by using the formulas obtained from previous studies (Berkeley model, 2020). As expected, the use of new technology and alternative fuel on airplanes can reduce air travel's costs and emissions. Furthermore, as expected, the renewably-powered hydrogen-electric aircraft competes well on certain routes highlighted in this research, particularly small routes, offering an economical alternative to current modes both in terms of time, money and availability of alternatives in the route. Finally, for H3 it is expected that the adoption of certain policy measures to correlate with increased cost-effectiveness of aircraft solutions, which supports H3. The model shows that based on modelled number of passengers and the technical data from company dialogues with Berkeley contributors, the ZeroAvia renewably–powered hydrogen–electric 19-seater HyFlyer can be more cost-competitive than the hybrid, the battery-electric aircraft and the traditional aircraft currently in use on the selected three reference routes, with cost-competitiveness over 90 to 100% of the studied aircraft. The renewably–powered hydrogen–electric aircraft is more emission-effective than the battery-electric based on modelled number of passengers and assumptions of hydrogen production from electrolysis. Including hydrogen fuel cells in the Norwegian mandate for sustainable aviation fuels can (a) strongly facilitate technology and industry development in Norway and (b) make more emission-effective aircraft even more cost-competitive.

8. Research Ethics, Limitations and Avenues for Future Research

"Where documents and presentations are used as secondary sources in an archival or documentary research strategy, their original purpose wasn't connected to this research and so as the researcher using this strategy, one needs to be sensitive to the nature and original purpose of the documents one selects, the way in which one analyzes them and the generalizations that can be draw" (Hakim, 2000). Hence, particular care has been taken when processing and evaluating the Berkeley model subsystems and files. The author would like to deeply thank the Berkeley contributors for their availability throughout this yearly project.

Some of the technical limitations were already presented under the analysis of reliability in this research. Further limitations include the use of only a limited number of aircraft technologies as well as a selected number of routes. Future studies could look into more routes, performing the same calculations taking into consideration country-specific context. As more and more country-specific studies are developed, the topic will take further global relevance.

There are many avenues for future research. Cost breakdown into cost categories can be refined. It is possible to build on the incentive model by continuing the study on low-carbon fuel standards (LCFS) implementation and the introduction of fuel cells into LCFS. Due to the limited timeframe of the project, the author hasn't taken direct contact with all aircraft manufacturers. Further cross-check of aircraft characteristics could further improve inter-rater reliability.

Bibliography

Introduction

Air Transport Action Group [ATAG]. (2019). Fact sheet #3 – Tracking aviation efficiency. Retrieved May 2021 from https://aviationbenefits.org/media/166506/fact-sheet_3_tracking-aviation-efficiency.pdf.

Alvestad, K., Haug, S. O., & Jikiun, S. P. (2020). A study of the potential for sustainable aviation in Norway (Bachelor's thesis, Høgskulen på Vestlandet). Retrieved May 2020 https://hvlopen.brage.unit.no/hvlopen-xmlui/bitstream/handle/11250/2679331/Alvestad_Haug_Jikiun.pdf?sequence=1.

Avinor (2017). The Full Story. Retrieved from https://avinor.no/globalassets/_b2b/facts-and-data/the-full-story/avinor_wr17_full_story.pdf, May 2021.

Avinor, SAS, Norwegian, NHO Luftfart og Widerøe (2011): Bærekraftig og samfunnsnyttig luftfart. Report 2. Aviation in Norway. Sustainability and social benefit.

Avinor, SAS, Norwegian og NHO Luftfart (2017): Bærekraftig og samfunnsnyttig luftfart. Report 3. Retrieved from https://www.nholuftfart.no/siteassets/bilder/barekraftig-og-samfunnsnyttig-luftfart.pdf, July 2020.

Avinor (March 2020). Forslag til program for introduksjon av elektrifiserte fly i kommersiell luftfart. Retrieved May 2020 from https://www.regjeringen.no/contentassets/048b277dfe9d4e76a059b0796bbe8b52/200305_rapport-elektrifiserte-fly-i-kommersiell-luftfart_final.pdf.

Avinor, SAS, Norwegian, NHO Luftfart, LO og Widerøe (October 2020): Bærekraftig og samfunnsnyttig luftfart. Report 4. Retrieved October 2020 from https://avinor.no/globalassets/_konsern/om-oss/rapporter/avinor_baerekraftsrapport_2020.pdf.

Avinor (2021). Retrieved May 2021 from: https://avinor.no/en/.

Cairns, R., CNN (2020). This aviation startup is soaring ahead with hydrogen-powered planes. Retrieved October 2020 from: https://edition.cnn.com/travel/article/zeroavia-zero-emission-hydrogen-planes-spc-intl/index.html.

Ghosh, I. (2021). Since 1850, these historical events have accelerated climate change. WEF. Retrieved May 2021 from https://www.weforum.org/agenda/2021/02/global-warming-climate-change-historical-human-development-industrial-revolution/.

Gössling, S., & Humpe, A. (2020). The global scale, distribution and growth of aviation: Implications for climate change. Global Environmental Change, 65, 102194. Retrieved May 2021 from https://doi.org/10.1016/j.gloenvcha.2020.102194.

Graver, B., Zhang, K., & Rutherford, D. (2019). CO2 emissions from commercial aviation, 2018. The International Council of Clean Transportation. Retrieved May 2021 from https://theicct.org/sites/default/files/publications/ICCT_CO2-commercl-aviation-2018_20190918.pdf.

ICAO (2016a). Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). Retrieved May 2021 from: https://www.icao.int/environmental-protection/CORSIA/Pages/default.aspx.

ICAO (2021a). World Aviation and the World Economy. Retrieved May 2021 from https://www.icao.int/sustainability/pages/facts-figures_worldeconomydata.aspx.

Lee, D. S., Fahey, D. W., Skowron, A., Allen, M. R., Burkhardt, U., Chen, Q., Doherty, S.J., Freeman, S., Forster, P.M., Fuglestvedt, J., Gettelman, A., De León, R.R., Lim, L.L., Lund, M.T., Millar, R.J., Owen, B., Penner, J.E., Pitari, G., Prather, M.J., Sausen, R. & Wilcox, L. J. (2021). The contribution of global aviation to anthropogenic climate forcing for 2000 to 2018. Atmospheric Environment, 244, 117834. Retrieved https://www.sciencedirect.com/science/article/pii/S1352231020305689?via%3Dihub May 2021.

Lian, J. I. (2007). Bærekraftig og samfunnsnyttig luftfart. Transportøkonomisk institutt. TØI-rapport 921/2007. Report 1. Retrieved from https://www.toi.no/getfile.php/138012-1201594173/Publikasjoner/T%C3%98I%20rapporter/2007/921-2007/921-sammendrag.pdf, July 2020.

Lian, J. I. (2010). Network dependency and airline competition–Consequences for remote areas in Norway. Journal of Air Transport Management, 16(3), 137-143. Retrieved July 2020 from https://doi.org/10.1016/j.jairtraman.2009.07.007.

Mahashabde, A., Wolfe, P., Ashok, A., Dorbian, C., He, Q., Fan, A., ... & Locke, M. (2011). Assessing the environmental impacts of aircraft noise and emissions. Progress in Aerospace Sciences, 47(1), 15-52. Retrieved July 2020 from https://doi.org/10.1016/j.paerosci.2010.04.003.

Michot, S., Stancioi, N., McMullan, C., Peeters, S., Carlier, S. (2003). AERO2k Flight Movement Inventory. Tech. Rep. EEC/SEE/2003/005. EUROCONTROL Experimental Centre, Bretigny-sur-Orge, France. Retrieved May 2021 from https://www.eurocontrol.int/node/9927.

NOU (2019). Fra statussymbol til allemannseie - norsk luftfart i forandring. Retrieved from https://www.regjeringen.no/contentassets/19a211ff48814d09b9939631924cf48d/no/pdfs/nou201920190022000dddpdfs.pdf, July 2020.

Olivier, J.G.J., Janssens-Maenhout, G., Muntean, M., & Peters, J.A.H.W. (2016). Trends in global CO2 emissions: 2016 report (European Commission, Joint Research Centre, Science for Policy Report No. 103428). Retrieved from http://edgar.jrc.ec.europa.eu/news_docs/jrc-2016-trends-in-global-co2-emissions-2016-report103425.pdf.

Penner, J.E., Lister, D., Griggs, D., Docken, D., MacFarland, M. (1999). Aviation and the Global Atmosphere. Cambridge University Press, New York. Retrieved May 2021 from https://archive.ipcc.ch/ipccreports/sres/aviation/index.php?idp=0.

Service, E. R. (1968-85). Primitive Culture. Britannica. Lifestyles & Social Issues - Sociology & Society. Retrieved May 2021 from https://www.britannica.com/topic/primitive-culture#ref581615.

Schefter, M., Bernard, M. R., Matcheck, N., Chen, S. G., Wald, M., Cao, L., Sharp, J. (2020) Sustainable Regional Aviation. Submitted in partial fulfillment of the requirements for CEE 256 - Transportation Sustainability, Spring 2020. Company dialogues with the key contributors.

Stoknes, P. E., Eliassen K. A. (2015). Science Based Activism, Festschrift to Jorgen Randers. Fagbokforlaget. Retrieved May 2021 from https://www.fagbokforlaget.no/Science-based-activism/I9788245018660.

Van Pham, V., Tang, J., Alam, S., Lokan, C., & Abbass, H. A. (2010). Aviation emission inventory development and analysis. Environmental Modelling & Software, 25(12), 1738-1753. Retrieved July 2020 from https://doi.org/10.1016/j.envsoft.2010.04.004.

Visitnorway (2020). Getting around by plane. Retrieved May 2021 from: https://www.visitnorway.com/plan-your-trip/getting-around/by-air/.

Vlek, S., & Vogels, M. (2000). AERO-aviation emissions and evaluation of reduction options. Air & Space Europe, 2(3), 41-44. Retrieved July 2020 from https://doi.org/10.1016/S1290-0958(00)80062-3.

Literature Review

Alvestad, K., Haug, S. O., & Jikiun, S. P. (2020). A study of the potential for sustainable aviation in Norway (Bachelor's thesis, Høgskulen på Vestlandet). Retrieved May 2020 https://hvlopen.brage.unit.no/hvlopen-xmlui/bitstream/handle/11250/2679331/Alvestad_Haug_Jikiun.pdf?sequence=1.

Avinor, SAS, Norwegian, NHO Luftfart, LO og Widerøe (October 2020): Bærekraftig og samfunnsnyttig luftfart. Report 4. Retrieved October 2020 from https://avinor.no/globalassets/_konsern/om-oss/rapporter/avinor_baerekraftsrapport_2020.pdf.

Bergthorson, J.M. (2018). Recyclable metal fuels for clean and compact zero-carbon power. Retrieved https://www.sciencedirect.com/science/article/pii/S0360128518300327, May 2021.

Calderwood, D. (2020). ZeroAvia secures backing for hydrogen-electric 19-seater. Retrieved https://www.flyer.co.uk/zeroavia-secures-backing-for-hydrogen-electric-19-seater/, May 2021.

CAPA – Centre for Aviation (2021). Europe leads world aviation towards net zero carbon emissions. Retrieved from https://centreforaviation.com/analysis/reports/europe-leads-world-aviation-towards-net-zero-carbon-emissions-553358, May 2021.

Carbon Engineering (2021). AIR TO FUELS. Retrieved May 2020 from https://carbonengineering.com/air-to-fuels/.

Deutsche Welle (2021). CORSIA: World's biggest plan to make flying green 'too broken to fix'. Retrieved May 2021 from https://www.dw.com/en/corsia-climate-flying-emissions-offsets/a-56309438.

Dorbian, C. S., Wolfe, P. J., & Waitz, I. A. (2011). Estimating the climate and air quality benefits of aviation fuel and emissions reductions. Atmospheric Environment, 45(16), 2750-59. Retrieved May 2021 from https://doi.org/10.1016/j.atmosenv.2011.02.025.

Dowling, (2021). Norway's plan for a fleet of electric planes. Retrieved May 2021 from https://www.bbc.com/future/article/20180814-norways-plan-for-a-fleet-of-electric-planes.

Elnett21 (2021). Avinor planlegger solcellepark. Retrieved May 2021 from https://www.elnett21.no/nyheter/avinor-planlegger-solcellepark.

Ekici, S., Orhan, İ., Karakoç, T. H., & Hepbasli, A. (2020). Milestone of greening the flight path: alternative fuels. In Sustainable Aviation (pp. 243-253). Palgrave Macmillan, Cham. Retrieved May 2021 from https://link.springer.com/chapter/10.1007/978-3-030-28661-3_12.

European Commission (2021). Reducing emissions from aviation. Retrieved May 2021 from https://ec.europa.eu/clima/policies/transport/aviation_en.

Eviation (2021): https://www.eviation.co/. Retrieved May 2021.

Faiz, A., Weaver, C. S., & Walsh, M. P. (1996). Air pollution from motor vehicles: standards and technologies for controlling emissions. World Bank Publications. Retrieved from https://books.google.no/books?hl=de&lr=&id=Hqsyv_KD0lgC&oi=fnd&pg=PR13&dq=faiz+et+al+1996&ots=Dg3zmtNO6l&sig=Vwvpqi-r70H_TSHvLlo_3I7Tum8&redir_esc=y#v=onepage&q=faiz%20et%20al%201996&f=false May 2021.

Faradair (2021): https://www.faradair.com/. Retrieved May 2021.

Gardner, R. M., Adams, K., Cook, T., Deidewig, F., Ernedal, S., Falk, R., ... & Van Drimmelen, R. (1997). The ANCAT/EC global inventory of NOx emissions from aircraft. Atmospheric Environment, 31(12), 1751-1766. Retrieved May 2021 from https://www.sciencedirect.com/science/article/abs/pii/S1352231096003287.

Gnadt, A. R., Speth, R. L., Sabnis, J. S., & Barrett, S. R. (2019). Technical and environmental assessment of all-electric 180-passenger commercial aircraft. Progress in Aerospace Sciences, 105, 1-30. Retrieved from https://doi.org/10.1016/j.paerosci.2018.11.002, July 2020.

Gössling, S., & Humpe, A. (2020). The global scale, distribution and growth of aviation: Implications for climate change. Global Environmental Change, 65, 102194. Retrieved May 2021 from https://doi.org/10.1016/j.gloenvcha.2020.102194.

Graver, B., Zhang, K., & Rutherford, D. (2019). CO2 emissions from commercial aviation, 2018. The International Council of Clean Transportation. Retrieved May 2021 from https://theicct.org/sites/default/files/publications/ICCT_CO2-commercl-aviation-2018_20190918.pdf.

Harris, M. (2021). ZeroAvia's hydrogen fuel cell plane ambitions clouded. Retrieved May 2021 from https://techcrunch.com/2021/04/14/zeroavias-hydrogen-fuel-cell-plane-ambitions-clouded-by-technical-challenges/.

ICAO (2005). The Manufacturers' Perspective. International Civil Aviation Day. Retrieved https://www.icao.int/secretariat/SecretaryGeneral/AviationDay/Documents/Presentations/ICCAIA.pdf, May 2021.

ICAO (2016b). Resolution A39-2: Consolidated statement of continuing ICAO policies and practices related to environmental protection – Climate change. Retrieved from https://www.icao.int/environmental-protection/documents/resolution_a39_2.pdf, May 2020.

ICAO (2019). Introduction to the ICAO Basket of Measures to Mitigate Climate Change. Retrieved May 2020 from https://www.icao.int/environmental-protection/Documents/EnvironmentalReports/2019/ENVReport2019_pg111-115.pdf.

ICAO (2021b). ICAO Global Coalition for Sustainable Aviation. Retrieved May 2021 from: https://www.icao.int/environmental-protection/SAC/Pages/learn-more.aspx.

IPCC (1996a). Climate change 1995. Impacts, adaptations and mitigation of climate change: scientific-technical analyses. Watson, R. T., Zinyowera, M. C., & Moss, R. H. Cambridge University Press. Retrieved May 2021 from https://books.google.no/books?id=JgphajrWfOsC&lpg=PP9&ots=NdHbHTolZ0&dq=Aviation%20and%20the%20Global%20Atmosphere%3A%20A%20Special%20Report%20of%20the%20&lr&hl=de&pg=PA288#v=snippet&q=IPCC,%201996a)&f=false.

IPCC (1996b). Technologies, Policies and Measures for Mitigating Climate Change-IPCC Technical Paper. November 1996 IPCC, 84. Retrieved May 2021 from https://books.google.no/books?id=JgphajrWfOsC&lpg=PP9&ots=NdHbHTolZ0&dq=Aviation%20and%20the%20Global%20Atmosphere%3A%20A%20Special%20Report%20of%20the%20&lr&hl=de&pg=PA288#v=snippet&q=IPCC,%201996a)&f=false.

Irfan, U. (2019). "Forget cars. We need electric airplanes. Retrieved May 2020 from Vox, https://www.vox.com/2019/3/1/18241489/electric-batteries-aircraft-climate-change.

Janić, M. (1999). Aviation and externalities: the accomplishments and problems. Transportation Research Part D: Transport and Environment, 4(3), 159-180. Retrieved May 2021 from https://doi.org/10.1016/S1361-9209(99)00003-6.

Lian, J. I. (2007). Bærekraftig og samfunnsnyttig luftfart. Transportøkonomisk institutt. TØI-rapport 921/2007. Report 1. Retrieved from https://www.toi.no/getfile.php/138012-

1201594173/Publikasjoner/T%C3%98I%20rapporter/2007/921-2007/921-sammendrag.pdf, July 2020.

Lyle, C. (2018). Beyond the ICAO's CORSIA: Towards a more climatically effective strategy for mitigation of civil-aviation emissions. Climate Law, 8(1-2), 104-127. Retrieved May 2021 form https://brill.com/view/journals/clla/8/1-2/article-p104_104.xml.

Mahashabde, A., Wolfe, P., Ashok, A., Dorbian, C., He, Q., Fan, A., ... & Locke, M. (2011). Assessing the environmental impacts of aircraft noise and emissions. Progress in Aerospace Sciences, 47(1), 15-52. Retrieved July 2020 from https://doi.org/10.1016/j.paerosci.2010.04.003.

Michot, S., Stancioi, N., McMullan, C., Peeters, S., Carlier, S. (2003). AERO2k Flight Movement Inventory. Tech. Rep. EEC/SEE/2003/005. EUROCONTROL Experimental Centre, Bretigny-sur-Orge, France. Retrieved May 2021 from https://www.eurocontrol.int/node/9927.

Nelson, E. S., & Reddy, D. R. (Eds.). (2018). Green aviation: reduction of environmental impact through aircraft technology and alternative fuels. CRC Press. Retrieved January 2021 from https://www.routledge.com/Green-Aviation-Reduction-of-Environmental-Impact-Through-Aircraft-Technology/Nelson-Reddy/p/book/9780367573041.

OECD (1997a). Special Issues in Carbon/Energy Taxation: Marine Bunker Fuel Charges. Working Paper 11. Annex I expert group on UNFCCC. Retrieved May 2021 from https://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?doclanguage=en&cote=ocde/gd(97)77. Organization for Economic Cooperation and Development, Paris, France, 79 pp.

OECD (1997b). Special Issues in Carbon/Energy Taxation: Carbon Charges on Aviation Fuels. Working Paper 12. Annex I expert group on the UNFCCC. Retrieved from https://www.oecd.org/officialdocuments/publicdisplaydocumentpdf/?doclanguage=en&cote=ocde/gd(97)78, May 2021. Organization for Economic Cooperation and Development, Paris, France. 67 pp.

Penner, J.E., Lister, D., Griggs, D., Docken, D., MacFarland, M. (1999). Aviation and the Global Atmosphere. Cambridge University Press, New York. Retrieved May 2021 from https://archive.ipcc.ch/ipccreports/sres/aviation/index.php?idp=0.

Schäfer, A. W., Barrett, S. R., Doyme, K., Dray, L. M., Gnadt, A. R., Self, R., ... & Torija, A. J. (2019). Technological, economic and environmental prospects of all-electric aircraft. Nature Energy, 4(2), 160-166. Retrieved May 2020 from https://www.nature.com/articles/s41560-018-0294-x.

Sgouridis, S., Bonnefoy, P. A., & Hansman, R. J. (2011). Air transportation in a carbon constrained world: Long-term dynamics of policies and strategies for mitigating the carbon footprint of commercial aviation. Transportation Research Part A: Policy and Practice, 45(10), 1077-1091. Retrieved May 2021 from https://doi.org/10.1016/j.tra.2010.03.019.

Schumann, U. (1993). On the effect of emissions from aircraft engines on the state of the atmosphere. Retrieved May 2021 from https://core.ac.uk/reader/30964530.

Sprinkle, C. H. and Macleod, K.J. (1993). Aviation and the Environment. Presented at the 5th International Conference on Aviation Weather Systems in Vienna. Published by the American Meteorological Society, Boston, pp. 89-91.

Timperley, J. (2020). Should we give up flying for the sake of the climate? BCC. Retrieved from https://www.bbc.com/future/article/20200218-climate-change-how-to-cut-your-carbon-emissions-when-flying, May 2021.

van der Sman, E. S., Peerlings, B., Kos, J., Lieshout, R., & Boonekamp, T. (2020). Destination 2050. Retrieved from https://reports.nlr.nl/bitstream/handle/10921/1555/NLR-CR-2020-510-public.pdf?sequence=4. May 2021.

Vlek, S., & Vogels, M. (2000). AERO-aviation emissions and evaluation of reduction options. Air & Space Europe, 2(3), 41-44. Retrieved July 2020 from https://doi.org/10.1016/S1290-0958(00)80062-3.

WMO (1995). Scientific assessment of ozone depletion, 1994 (No. 37). United States. Office of Mission to Planet Earth. World Meteorological Organization. Retrieved from https://library.wmo.int/index.php?lvl=notice_display&id=15449#.YLTpX5Mzau4, May 2021.

ZeroAvia (2021): https://www.zeroavia.com/. Retrieved May 2021.

Methodology

Alvestad, K., Haug, S. O., & Jikiun, S. P. (2020). A study of the potential for sustainable aviation in Norway (Bachelor's thesis, Høgskulen på Vestlandet). Retrieved May 2020 https://hvlopen.brage.unit.no/hvlopen-xmlui/bitstream/handle/11250/2679331/Alvestad_Haug_Jikiun.pdf?sequence=1.

Avinor (2017). Avinor and Norwegian Aviation 2017. Retrieved May 2021 from https://avinor.no/globalassets/_konsern/om-oss/rapporter/en/avinor-rapport_uk_v1.pdf.

Avinor, SAS, Norwegian, NHO Luftfart, LO og Widerøe (October 2020): Bærekraftig og samfunnsnyttig luftfart. Report 4. Retrieved October 2020 from https://avinor.no/globalassets/_konsern/om-oss/rapporter/avinor_baerekraftsrapport_2020.pdf.

CAPA – Centre for Aviation (2021). Europe leads world aviation towards net zero carbon emissions. Retrieved from https://centreforaviation.com/analysis/reports/europe-leads-world-aviation-towards-net-zero-carbon-emissions-553358, May 2021.

Olsen, K. M. (2020). Research Design. Retrieved from STR402A-H20, Methodology for Master Thesis, Norwegian School of Economics, Canvas, https://nhh.instructure.com/.

Saunders, M., Lewis, P., & Thornhill, A. (2016). Research methods for business students (Seventh). Nueva York: Pearson Education.

Tranøy, K.E., ‘induktive metoder’, Store norske leksikon. Nov. 17, 2017, Accessed: Feb. 24, 2020. [Online]. Retrieved December 2020: http://snl.no/induktive_metoder.

High-level Emission and Cost Reduction for Aviation (HECRA) Model, Data and Assumptions

CAPA – Centre for Aviation. European Airline Margin 2019. Retrieved May 2020 from https://centreforaviation.com/analysis/reports/european-airline-margin-charts-wizz-air-could-take-1-from-ryanair-479002.

California State Portal (2021). www.ca.gov.

Cazel, P. (2018). Creating Dedicated Renewable Hydrogen Supply. California Energy Commission. Retrieved May 2021 at https://cafcp.org/sites/default/files/OCT17-EB-4_H2Production-CEC-Baronas.pdf. Retrieved April 2021.

Elofsson, A., Smedby, N., Larsson, J., & Nässén, J. (2018). Local governance of greenhouse gas emissions from air travel. Journal of Environmental Policy & Planning, 20(5), 578-594.

Ghandehariun, S., & Kumar, A. (2016). Life cycle assessment of wind-based hydrogen production in Western Canada. International Journal of Hydrogen Energy, 41(22), 9696-9704.

ILO (2019). Norway (2019) according to Global Wage Report, International Labor Organisation. Retrieved May 2021 from https://www.ilo.org/wcmsp5/groups/public/---dgreports/---dcomm/---publ/documents/publication/wcms_762534.pdf.

Motazedi, K., Salkuyeh, Y. K., Laurenzi, I. J., MacLean, H. L., & Bergerson, J. A. (2021). Economic and environmental competitiveness of high temperature electrolysis for hydrogen production. International Journal of Hydrogen Energy.

Ozbilen, A., Dincer, I., & Rosen, M. A. (2013). Comparative environmental impact and efficiency assessment of selected hydrogen production methods. Environmental Impact Assessment Review, 42, 1-9.

Widerøe (2021). www.wideroe.no.

Analysis and Discussion

EASA (2020). EASA certifies electric aircraft, first type certification for fully electric plane world-wide. Retrieved May 2020 from: https://www.easa.europa.eu/newsroom-and-events/press-releases/easa-certifies-electric-aircraft-first-type-certification-fully.

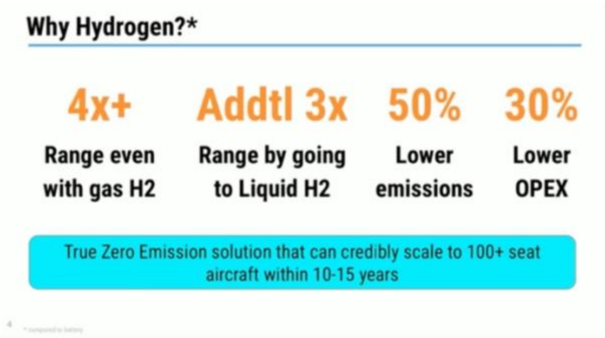
Posada, J. (2017). Advances challenges and future of all-electric aircraft. In Proceedings of the 7th European Conference for Aeronautics and Space Sciences. EUCASS. Retrieved May 2021 from https://www.eucass.eu/doi/EUCASS2017-676.pdf.

Research Ethics, Limitations and Avenues of Future Research

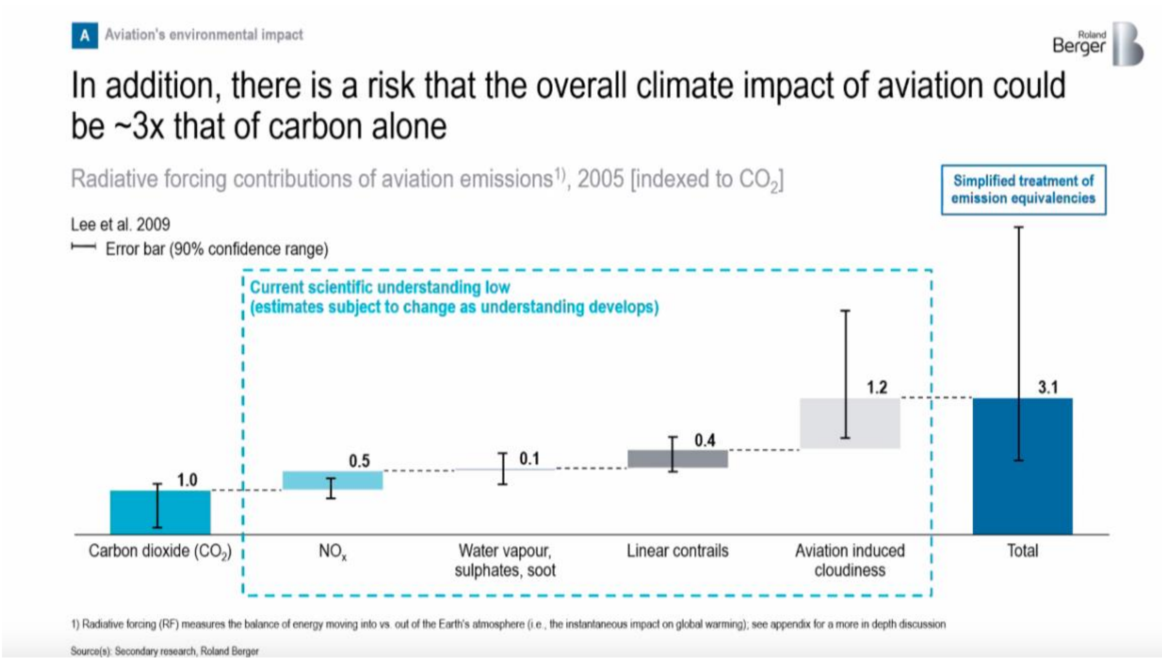
Hakim, C. (2000) Research Design: Successful Designs for Social and Economic Research (2nd edn). London: Routledge.

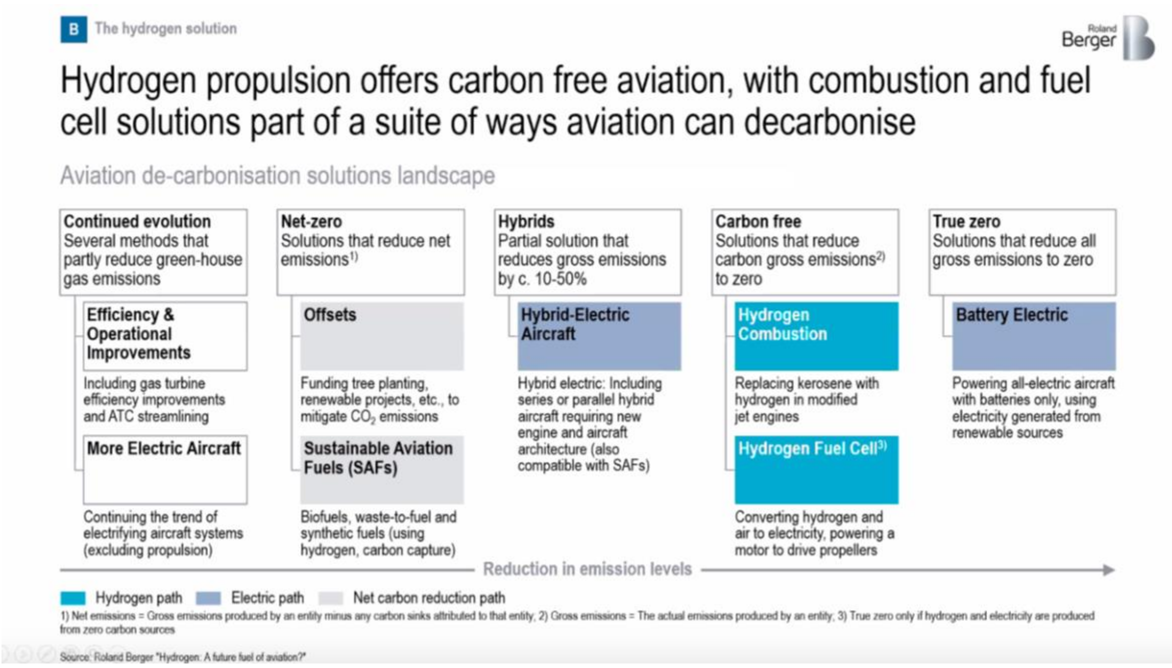
Appendix

Relevant contributions from the Norwegian Hydrogen Conference, June 2020



Relevant contributions from First International Hydrogen Aviation Conference, Sept 2020




B The hydrogen solution
Roland Berger
Hydrogen propulsion offers carbon free aviation, with combustion and fuel cell solutions part of a suite of ways aviation can decarbonise
Aviation de-carbonisation solutions landscape
Continued evolution
Several methods that partly reduce green-house gas emissions
Efficiency & Operational Improvements
Including gas turbine efficiency improvements and ATC streamlining
More Electric Aircraft
Continuing the trend of electrifying aircraft systems (excluding propulsion)
Net-zero
Solutions that reduce net emissions[1]
Offsets
Funding tree planting, renewable projects, etc., to mitigate CO_2 emissions
Sustainable Aviation Fuels (SAFs)
Biofuels, waste-to-fuel and synthetic fuels (using hydrogen, carbon capture)
Hybrids
Partial solution that reduces gross emissions by c. 10-50%
Hybrid-Electric Aircraft
Hybrid electric: Including series or parallel hybrid aircraft requiring new engine and aircraft architecture (also compatible with SAFs)
Carbon free
Solutions that reduce carbon gross emissions[2] to zero
Hydrogen Combustion
Replacing kerosene with hydrogen in modified jet engines
Hydrogen Fuel Cell[3]
Converting hydrogen and air to electricity, powering a motor to drive propellers
True zero
Solutions that reduce all gross emissions to zero
Battery Electric
Powering all-electric aircraft with batteries only, using electricity generated from renewable sources
Reduction in emission levels
Hydrogen path
Electric path
Net carbon reduction path
1) Net emissions = Gross emissions produced by an entity minus any carbon sinks attributed to that entity; 2) Gross emissions = The actual emissions produced by an entity; 3) True zero only if hydrogen and electricity are produced from zero carbon sources
Source: Roland Berger "Hydrogen: A future fuel of aviation?"