A Study of the Potential for Sustainable Aviation in Norway

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Preface

This thesis is written on behalf of the Department of Mechanical and Marine Engineering at Western Norway University of Applied Sciences (HVL), as a Bachelor of Science degree in the study field of Energy Technology. The internal academic supervisor from HVL is Professor Richard J. Grant. The purpose of this thesis is to look at the potential for sustainable aviation in Norway. The subject was assigned by ourselves, since we found the topic highly relevant and interesting to tackle from an engineering perspective.

The extraordinary circumstances surrounding the outbreak of COVID-19 during the process of writing lead to a drastic change in both the internal and external work. The communication and group dynamic were challenged by the restrictions imposed on the society. Luckily, the methodology of the thesis was mostly based on literature searches, without the need for laboratory tests or experiments. This proved to be an advantage for the project.

We would like to thank our internal supervisor, Professor Richard J. Grant, for his help and guidance throughout this project. We would like to thank Helge Eidsnes (Avinor) for his expertise in aviation. We also want to thank Kristian Holmefjord (Corvus Energy) for his expertise in batteries, and Velaug Myrseth Oltedal (HVL) for her proficiency in hydrogen technology. Furthermore, we would like to thank Harald Johnsen (Widerøe Ground Handling); and former and current pilots who have supported us through constructive feedback and valuable input. We specifically would like to thank all the people who have helped and supported us, in any way, through providing data and sharing their knowledge regarding this topic.

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Abstract

The aviation sector is a key contributor to global greenhouse gas emissions today. The sustainability movement has led to emission-reducing measures in other parts of the transport sector, but efforts to make aviation more sustainable have not been as pervasive. Challenges related to a lower specific energy density of alternative sustainable energy sources compared to aviation fuel, has led to problems related to weight which in turn affects the aircraft's range. The aim of this project is to investigate how the aviation sector in Norway can become more sustainable, considering the current demand, status, and feasibility of present technologies.

The technology status is addressed through a review of the history of sustainable aviation and current projects. Various forms of energy storage and propulsion systems related to batteries, hydrogen, and biofuel are reviewed. In a case study, potential routes in Norway that have the potential to be covered by aircraft with sustainable propulsion are studied. The route between Bergen and Stavanger is selected from the short-haul network due to passenger numbers and demand. A 19 seat aircraft of the type DHC-6-400 Twin Otter is selected due to weight savings associated with fewer crew members and no requirement of lavatories. Furthermore, the fuel requirement based on the weight of the aircraft with passengers and luggage is used to calculate the required amount of energy for three potential alternative propulsion systems; electric, hydrogen, and hybrid electric. Related to this, topics such as weight savings, efficiency, heating, and battery capacity are also addressed. In addition, consideration is made regarding aircraft certification and also airport.

It is found that more sustainable aircraft will have challenges related to today's battery technology, where electrical propulsion will be difficult to implement. With a hydrogen propulsion system, both weight and volume for different storage methods will result in challenges. With the right ratio between fuel and battery, hybrid electric propulsion will be feasible. In addition, a supportive infrastructure needs to be implemented, and the certification process should facilitate more sustainable types of propulsion systems.

Sammendrag

I dag medfører luftfartssektoren høye utslipp globalt. Det grønne skiftet har ført til omstillinger i andre deler av transportsektoren, men forsøk på å gjøre luftfarten mer bærekraftig har ikke vært like gjennomgripende. Utfordringer knyttet til lavere spesifikk energitetthet for alternative bærekraftige energibærere sammenliknet med flydrivstoff, medfører problemer knyttet til vekt som igjen påvirker flyets rekkevidde. Målet med dette prosjektet er å undersøke om luftfartssektoren i Norge kan bli mer bærekraftig, sett i lyset av dagens etterspørsel, status og gjennomførbarhet av nåværende teknologier.

I et litteratursøk skal teknologistatusen adresseres ved hjelp av en gjennomgang av historien bak bærekraftig luftfart og aktuelle prosjekter. Forskjellige former for energilagring og fremdriftssystemer knyttet til batterier, hydrogen og biofuel gjennomgås. I et case-studie undersøkes flyruter i Norge som potensielt kan dekkes av bærekraftig fremdrift. Ruten Bergen-Stavanger velges ut ifra kortbanenettet på grunnlag av passasjertall og etterspørsel. Et 19 seters fly av typen DHC-6-400 Twin Otter velges på grunnlag av vektbesparelser knyttet til reduksjon av kabinbesetning og toalettfasiliteter. Videre genereres mengden drivstoff på grunnlag av vekten på flyet med passasjerer og bagasje, og dette brukes til å kalkulere nødvendig energimengde for tre potensielle fremdriftssystemer; elektrisk, hydrogen og hybridelektrisk. Knyttet til dette vil temaer som vektbesparelser, virkningsgrader, oppvarming og batterikapasitet også bli tatt opp. I tillegg er sertifisering av fly og infrastruktur viktige eksterne faktorer.

Det ble funnet at flyet vil ha utfordringer knyttet til dagens batteriteknologi, hvor elektrisk fremdrift vil være vanskelig å gjennomføre. Med hydrogen som fremdrift vil både vekt og volum for forskjellige lagringsmetoder medføre problemer. Ved et riktig forhold mellom drivstoff og batteri kan hybridelektrisk fremdrift være gjennomførbart. I tillegg bør en støttende infrastruktur implementeres, og sertifiseringsprosessen tilrettelegges for mer bærekraftige fremdriftssystemer.

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Abbreviations

73H	Boeing 737-800
73G	Boeing 737-700
AC	Alternating Current
AFC	Alkaline Fuel Cell
Ah	Ampere hour
Al-ion	Aluminium-ion battery
AlO_2	Aliminium-air battery
APU	Auxillary Power Unit
A_{sweep}	Relevant cross-sectional area
BGO	Bergen
BoP	Balance of Plant
°C	Celsius degree
CAA	Civil Aviation Authority
CAeS	Cranfield Aerospace Solutions
CEO	Chief Executive Officer
CGH_2	Compressed Gaseous Hydrogen
CR9	Bombardier Regional Jet 900
DC	Direct Current
DH3	De Havilland Canada DHC-8-300 Dash 8Q
DH4	De Havilland Canada DHC-8-400 Dash 8Q
EASA	European Union Aviation Safety Agency

ENBR	Bergen
ENHD	Haugesund
ENZV	Stavanger
EV	Electric Vehicle
eVTOL	electric TakeOff and Landing
EU	European Union
F	Force
FAA	Federal Aviation Administration
FAME	Fatty Acid Methyl Ester
GHG	Greenhouse gas
HEFA	Hydrotreated Esters and Fatty Acids
hp	Horsepower
HVL	Western Norway University of Applied Sciences
IATA	International Air Transport Association
Incl.	Included
ICAO	International Civil Aviation Organization
K	Kelvin
kg	Kilogram
kt	Knots
ktas	True air speed (knots)
kW	Kilowatt
kWh	Kilowatt hour

L	Length between the wings of an aircraft from tip to tip
lbs	Pounds
LH_2	Liquid Hydrogen
LIB	Lithium-ion battery
$LiCoO_2$	Lithium Cobalt Oxide
$LiFePO_4$	Lithium Iron Phosphate
$LiMnO_2$	Lithium ion Manganese Oxide
$LiNiCoMnO_2$	Lithium Nickel Manganese Cobalt Oxide
LiNi	Lithium-Nickel battery
LiO_2	Lithium-Air
LiS	Lithium-Sulphur battery
LNG	Liquid Natural Gas
LOHC	Liquid Organic Hydrogen Carrier
m	Meter
$\dot{m}_{air}$	Mass flow rate
MCFC	Molten Carbonate Fuel Cell
MLW	Maximum landing weight
MTOW	Maximum takeoff weight
NiCd	Nickel-cadmium
nm	Nautical mile
p.	Page
P	Power

PAFC	Phosphoric Acid Fuel Cell
Pax	Passenger
PLF	Passenger load factor
PEMFC	Proton Exchange Membrane Fuel Cell
PSO	Public Service Obligation
RFID	Radio-frequency identification
SAS	Scandinavian Airlines System
shp	Shaft Horsepower
SiO_2	Silicon-air battery
SOFC	Solid Oxide Fuel Cell
SSB	Solid-state battery
SVG	Stavanger
t	Time
T/O mass	Takeoff mass
TU-155/154	Tupolev Tu-155/154
UN	United Nations
V	Volt
v_{flight}	Velocity of flight
W	Work
W	Watt
η	Efficiency
Δx	Distance over which a force act

Δv_z	The downward velocity of air (that the aircraft pushes downward)
ρ_{air}	Density of air

1. Introduction

The restlessness of mankind has challenged the norms of individual and geographic mobility for as long as one can remember. From the domestication of draft animals and the art of seamanship dating several millennia back in time, to the invention of the piston engine during the industrial revolution [1]. Regardless of the era, there has always been a strong driving force for the development of transportation. The internal combustion engine certainly gave an advance to the industry with its adaptability for different applications and increasing global accessibility. In addition, the then-so-abundant energy source of petroleum allowed for a massive growth in the energy sector. On the flip side, the heavy reliance on fossil fuels also meant an increase in global GHG emissions. Today, over 200 years since the beginning of the industrial revolution, the world is facing the consequences of climate change as a result.

In order to sustain future generations, several attempts have been made to encourage a transition to renewable energy sources, also in the transportation sector. Electric vehicles (EV) such as cars, buses, trains and, just recently, marine vessels have successfully been introduced to the market. Although the internal combustion engine still dominates the transportation sector, new technology innovations indicate that the industry is on a path towards a green shift.

This project will take a closer look at how the aviation industry can cater for future generations by reducing its carbon footprint. A future implementation of more sustainable aircraft propulsion would be challenging the norms of commercial air traffic. Different aspects to this technology need to be further investigated in order to identify how the industry can accommodate such a transition.

First, an analysis of the challenges related to making aviation more sustainable will be made in Chapter *2 Literature study*. This particularly consider the fields of available technologies, energy storage, propulsion methods, certification processes and the global availability of resources. The embryonic history of sustainable aviation, and the potential energy storage methods such as batteries, hydrogen and biofuels, and different propulsion systems will be reviewed. Secondly, these perspectives will be directed towards the short haul network in Norway in Chapter *3 Case Study*, where issues connected to the future of green aviation in Norway will be explored. A specific route and aircraft type will be selected as a test bed, in order to determine whether sustainable propulsion will be feasible. Topics such as weight savings, efficiencies, propulsion and technical challenges of creating a supporting infrastructure will be explored in connection with the given route conditions. The results will follow in Chapter *4 Results* where the necessary calculations are displayed. A discussion in Chapter *5 Discussion* will bring forward new perspectives that were not brought up earlier in this thesis. Lastly, Chapter *6 Conclusion* will draw the conclusions and highlight suggestions for the way forward in the wake of this study.

1.1 Aim and objectives

The aim of this project is;

Can the aviation sector in Norway become more sustainable, considering the current demand, status and feasibility of present technologies?

In order to answer this question, the following objectives will be explored;

1. To review the current technology status for the potential of electric and hybrid-electric flights.
2. To inspect current and future battery technologies and the energy density compared to jet fuel.
3. To investigate the potential of electric and hybrid electric systems in aircraft.
4. To map out routes in the short haul network in Norway that has the potential to be replaced by electric aircraft and initially explain why Bergen-Stavanger is an ideal route to look at.
5. To identify the viability of electric and hybrid electric flights between Bergen-Stavanger before 2030.
6. To discuss other possibilities such as hydrogen and biofuel.

1.2 Sources of error

- Factors such as drag and friction are neglected.
- The balance of the plane is neglected.
- The fuel requirement will be affected by the weather conditions and can therefore vary.
- The volumetric density of batteries are not taken into account.
- The weight of LH_2 tanks are not taken into account.
- Assumptions for efficiency, weight, weight reductions, specific energy of SSB batteries and turn-around time have been made.
- Calculations for the weight of the aircraft is based on two different sources; RoucketRoute and Viking Air’s website.

- The discount of energy need under weight reduction assumptions for calculations of electric, hybrid and hydrogen porpulsion is neglected since the battery and hydrogen weight remain the same.
- Investment and operational costs are not considered.
- Energy losses connected to the balance of plant of the a fuel cell is neglected.

1.3 Conversion data

The following units for conversion have been used in the calculations of this thesis;

Table 1 – List of convertion units and contents.

Weight units	**Conversion**
kg	1.00
lbs	2.2054
Velocity units	**Conversion**
m/s	1.00
km/h	3.6
kt	1.9438
Length units	**Conversion**
m	1.00
nm	0.00054
ft	3.2808
Volume units	**Conversion**
l	1.00
US gal	0.2642
Temperature units	**Conversion**
ºC	0.00
K	273.15
Energy units	**Conversion**
J	1.00
Wh	0.00029
Energy content	**Specific energy (MJ/kg)**
Hydrogen	119.96
Jet A-1 fuel	43.02

1.4 Research methodology

This project is primarily a qualitative study [2], which is a method where data is collected through document analysis and observations. First, a literature study is conducted, where relevant literature such as reports, papers, textbooks and articles are reviewed. Secondly, a case study is conducted in order to substantiate the literature study. Relevant theory and findings from the literature study are used to make the case study.

1.4.1 Literature study

A literature study has initially been conducted to give the thesis a grounding in the state-of-the-art that surrounds the topics pertinent to realising the development of a sustainable future for aviation. This is to give the reader a foundation for the topics that will be discussed later, and also to enable an assessment of proposed technical solutions to be made in an evidenced way. It will additionally help the reader, from a non-aviation background with some of the theory concepts and terminology. A theoretical basis is, therefore, essential for analysing the findings. Relevant information from a wide variety of sources is used to create a sufficient scope. Search engines such as Google Scholar, Web of Science, Engineering Village and Oria are used for information gathering. The first three search engines are accessible and internationally recognised for holding academic and scientific content. Google Scholar covers recent academic publications online. Engineering Village is a resource for information directed towards engineers, giving the reader access to different academic papers, books, journals and pages. Oria is the search engine from the library of HVL. Sources from the publications found are also further investigated to test if the original source is valid. Examples of common search words are “sustainable,” “electric” and “hybrid electric” combined with “aircraft,” “propulsion” and “plane.” Other search words were “hydrogen,” “biofuel” and “solid state battery.”

Considering that the technology around sustainable aviation is rigorously in development, the available information around this field is restricted. Therefore, articles from newspapers, magazines and web pages are essential to take into account, in addition to the search engines mentioned. This is necessary because there are always new statements in the media about different projects under development within the sustainable field of aviation. Nevertheless, it is vital to stay critical to these types of sources. They can be rooted in visions, missions, values and long-term strategies of both startups and larger companies. The reliability of these ideas and ambitions for the future is uncertain. Many articles in the media often display a milestone, but without presenting the strategy on how to get there. The literature study can be found in Chapter 2, where relevant theory for addressing the issues of the thesis is presented.

1.4.2 Case study

The inductive method takes data from empiricism to draw a general conclusion to a problem [3]. Empiricism refers to observations and experiments from real life, which in this case corresponds to the information gathered in the literature study. Since the reality of this case originates from a rather unexplored field, little has yet been done to apply this technology to the commercial industry. One could, therefore, argue that the study should be approached from a deductive perspective, because the empirical evidence is of limited extent since the literature study is predominantly reviewing theory. The deductive method looks at the theory around a problem and uses numerical data and statistical methods in order to reach a conclusion, which corresponds to a quantitative study method. Nevertheless, the inductive method will be used to solve this case because it is strongly connected to a qualitative research method and allows for greater flexibility when collecting data, compared to its opposer. The exploratory arrangement of the inductive method allows the researcher to draw new observations from already existing evidence.

Bearing this in mind, the case study will review the network of short-haul flights in Norway in order to find a route that will act as a testbed for a potential replacement of fossil aircraft propulsion systems with a more sustainable alternative. Annual passenger numbers from commercial airline traffic will be used as a basis to identify the need for a sustainable replacement, and concrete alternatives will be explored, compared and discussed. Lastly, a conclusion will follow suggesting what the most feasible option is. Excel has been used for calculations and processing of collected data, and the flight planning program RocketRoute has been used to estimate fuel numbers for the aircraft.

2. Literature study

A transition to renewable energy sources still remains for the aviation sector, as it accounted for 2 % of global CO_2 emissions in 2017 [4]. The same year, former CEO of Boeing, Dennis Muilenburg, claimed that less than 20 % of the global population had taken a flight [5]. Other news agencies also stood behind this statement [6] [7]. Another news agency claimed that only 5-10 % of the global population flies during a given year [8]. Despite these estimates, there are no accurate statistics of the exact people who fly per year.

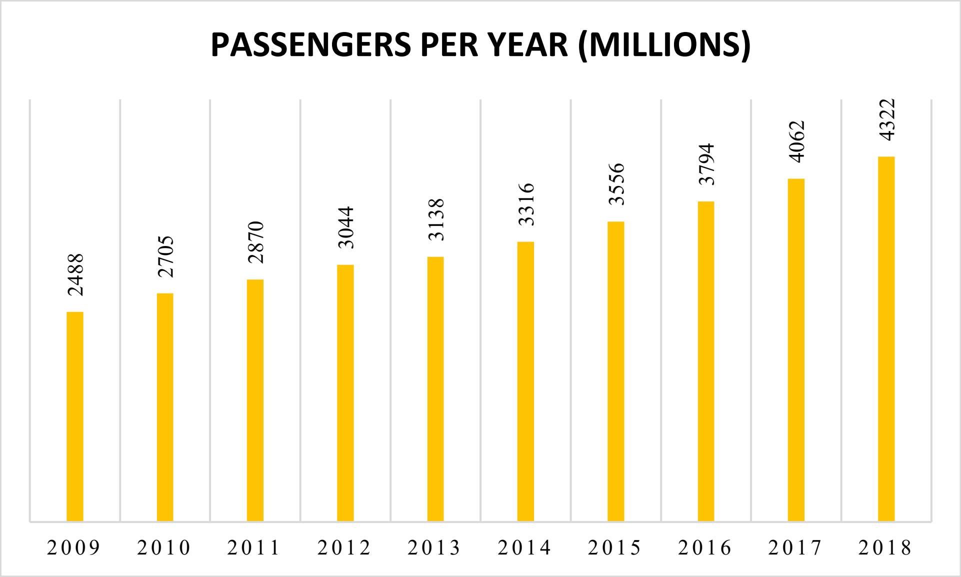


Figure 1 – Passengers per year, from ICAO's Annual Report 2018.

Figure 1 [9] shows the number of global passenger movements per year. The number of travelers has increased rapidly, with almost 74 %, over the course of 10 years. In 2018, the total passenger movements corresponded to more than half of the world's population. In the beginning of 2020, there was little evidence that this number would stagnate in the near future due to population growth together with an increasing economic prosperity in developing countries [10]. However, the global pandemic of COVID-19 has, at the time of writing, impacted the global economy to a great extent. Govenments have imposed international travel restrictions, and, as the global population are becoming less and less mobile in order to maintain low infection rates, airlines are facing a difficult time with historically low passenger numbers. This will certainly affect the data in Figure 1 for years to come.

In a press release in October 2018, IATA revealed statistics from their 20-Year Air Passenger Forecast [11], which is a prediction of global passenger numbers for the two upcoming decades. The report predicts an annual growth rate of 3.5 % if the policy framework of today remains unchanged, and that passenger numbers might double to 8.2 billion in 2037. This is especially due to an increasing middle class in countries with a recent advanced economic development such as India, Brazil, Russia and the Asia-Pacific region [7].

Action needs to be taken in order to reduce emissions, which will only increase in line with the vast growth of future travelers. Research and innovation are only part of the answer to the problem. Advocacy and policymaking will set the actual framework and regulations for the future of an industry where passenger safety is of high priority. The literature study will, therefore, explore future available technologies and key components in aircraft for more sustainable propulsion systems.

2.1 Technology status

Defining sustainable aviation is the first step in the direction of identifying the technology status on this very topic. To be sustainable is to meet the needs of today without impairing the opportunities of future generations [12]. In this project, sustainable aviation covers all zero emission propulsion systems for aircraft. That means aircraft powered by an electric motor, which receives electrical energy from a secondary source such as a battery or a hydrogen fuel cell [13][14] (p. 1). Following the definition, the resources used in the components should be extracted from nature moderately, and the manufacturing process should be in humane conditions. 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 [15]. Therefore, the term sustainable aviation will be used in a broader sense in this project, including hybrid electric propulsion [16] and biofuels [17] in addition.

It is essential to mention that the airport industry itself accounts for 5 % of the emissions from the aviation sector [18] and, therefore, also contributes to the problem. However, the main focus will lie in the aircraft propulsion system.

2.1.1 A brief history

The discovery of hydrogen as lifting power for balloons, and later airships, lead to inventions of airborne transportation in the late 18th century [19] (p. 4). The history of sustainable aviation can be traced back to October 1883, when the first flight with an airship powered by electric propulsion took place [20] (p. 292). However, it had a reduced range compared to other airships at the time. Airships were to dominate airborne transportation over the course of the next decades until the airplane eventually became its successor, gradually increasing in popularity commercially in the 1920s and 1930s [15].

The first manned electric flight took place in 1973 by the motor glider Militky MB-E1, a Brditschka HB-3 converted to electric propulsion [21] (p. 68). The test flight lasted for approximately 5 minutes, with a seating capacity of one pilot and one passenger. Just a few years after this breakthrough, the first manned solar powered flight was made by the Mauro Solar Riser in 1979 [21] (p. 80). The one-pilot aircraft flew a distance of 0.8 km and climbed to the altitude of 12 meters. A series of different electric propulsion prototypes have been built since then. Russian aircraft manufacturer Tupolev started the development of the experimental aircraft Tu-155, motivated by the increasing oil scarcity in the 1980s [22]. One of the three turbofan engines on their passenger plane Tu-154 was modified to run on both LH_2 and LNG. The aircraft started test flying on LH_2 in 1988 and performed its first flight on LNG the year after. Although the project was discontinued, the Tu-155 acquired around 100 flight hours [23].

Another milestone was achieved in 2008, when Virgin Atlantic's Boeing 747 embarked on the world's first test flight using biofuel [24]. One of the four engines of the plane ran on a mix of 20 % biofuel and 80 % aviation fuel on the journey from London to Amsterdam. Nevertheless, the first biofuel-powered commercial flight did not take place until 2011 when a Boeing 737-800 operated by KLM flew from Amsterdam to Paris [25]. Today, biofuels are of increasing use in the aviation sector, due to it currently being one of few options that can reduce the carbon footprint of a flight [26].

Figure 2 – Solar Impulse.

The 2010s was also a decade for records set by solar powered aircraft. The unmanned aircraft QinetiQ Zephyr stayed airborne for 14 days, due to its rechargeable batteries powered by solar cells [27]. In 2016, the Swiss made aircraft Solar Impulse made the first solar powered, one-pilot flight around the world [28]. With a wingspan of 72 meters, which exceeds that of a Boeing 747, the area on the wings was essential to accommodate the photovoltaic cells as the only energy supply onboard. Despite its illustrated as seen in Figure 2 [29], the aircraft weighed only 2.4 tonnes.

In 2007, Slovenian aircraft manufacturer Pipistrel made their first test flight with the 2-seat self launching electric glider Taurus Electro, which later on became the first electric aircraft available on the commercial market [30]. The January 2020 edition of Aerospace Magazine from the Royal Aeronautical Society mentioned ten ongoing electric aircraft projects from around the world [31]. In addition, there are a significant amount of manufacturers and companies that declare that they will to contribute to the sustainable and zero emission movement within airborne transportation in one way or another. More recent and improved technologies have allowed for prototypes with a higher seating capacity and longer range.

2.1.2 Current projects

Table 2 [32] shows a list of current electric and hybrid electric aircraft projects. Most of the projects mentioned are under development, used for demonstration, or not yet intended for series production. Not all projects will be elaborated on; only the most relevant ones. This is due to there being a lot of similar sustainable aircraft in development.

Figure 3 – HY4.

A smaller proportion of the listed projects are using hydrogen for propulsion. In 2016 the HY4, as seen in Figure 3 [33], had its first official flight [33]. The project was led by the German Aerospace Center, and among their partners was aircraft manufacturer Pipistrel and fuel cell manufacturer Hydrogenics. The aircraft is built with a twin fuselage where each hull accommodates two passengers. A hydrogen tank and battery are placed in each respective fuselage, and the electric motor is located between in a separate nacelle [34].

NASA is currently funding the University of Illinois in the research of a cryogenic hydrogen fuel cell system for commercial air transportation [35]. The project was started in 2019 and will continue for three years [36]. The aim is to investigate how liquid hydrogen can be used in aircraft to generate electric power for propulsion. Another company that aims to pursue hydrogen propulsion is US based ZeroAvia [37]. Their prototype is a Piper M-Class running on compressed hydrogen, which made its first test flight in 2019 after receiving permission for experimental research and development from the FAA.

Lastly, Alaka'i Technologies' Skai is challenging the norms of flying by not only choosing liquid hydrogen as an energy carrier, but also creating a vehicle that can takeoff and land vertically [38]. This makes Skai more adaptable to a variety of landing conditions such as urban areas or heliports. The vehicle can accommodate five passengers and one pilot, making Skai the equivalent to an airborne taxi [39]. This type of vehicle is also known as an eVTOL, an abbreviation for electric Vertical TakeOff and Landing.

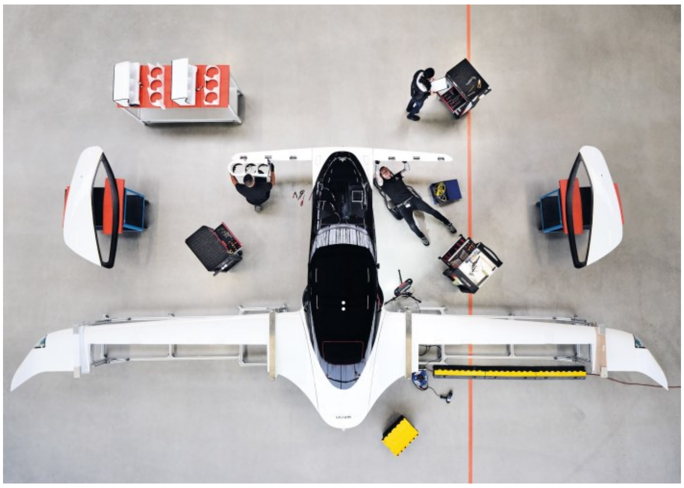


Figure 4 – Lilium Jet.

There are currently several eVTOLs in development, especially in the United States. Uber has launched the project Elevate, which aims to offer air taxis commercially by 2023. The service is often targeted towards individuals who want a private mobility experience while escaping road traffic in urban areas. Uber Elevate have already accumulated several partners [40], such as Pipistrel 801 eVTOL [41], Joby Aviation S4 [42], Aurora PAV [43], Jaunt Air Mobility [44], Overair Butterfly [45], Bell Nexus 6HX [46] and EmbraerX [47]. In 2019, the all-electric Lilium Jet, as Figure 4 [48] shows, started testing [49]. One of the Lilium prototypes, however, was severely damaged during maintenance work at the end of February 2020 [50]. Yet another eVTOL is the TriFan 600 by XTI Aircraft Company, which is expected to test fly in 2024 [51]. Its three ducted fans provide vertical lift and rotate 90 degrees to give horizontal propulsion. With a seating capacity of one pilot and five passengers, the TriFan 600 is similar to the Skai and Lilium Jet, allowing for shorter flights for private purposes.

One of the more promising all-electric projects is the prototype Alice, shown in Figure 5 [52], by the Israeli manufacturer Eviation [53]. The electric 9 seater was purposely designed and built, unlike similar projects involving electrification of a larger aircraft where an existing plane is used as a testbed. Unfortunately, an external battery package set the aircraft on fire during ground testing in January 2020 [54]. This was a significant setback for the project, and there is uncertainty about when the aircraft will be able to fly.

Figure 5 – Eviation Alice at Paris Air Show 2019.

Several other electric aircraft have been tested over the last decade, such as DA36 ESTAR 2 [55], Extra 330LE [56] and Liaoning Ruixiang RX1E [57]. American manufacturer Bye Aerospace launched the all-electric eFlyer 2 in 2018 [58]. The 2-seater was initially created for pilot training and is now available for purchase to the public. Other electric aircraft projects also plan to start testing in the next few years. NASA will continue structural ground testing on their experimental model X-57 Maxwell in 2020 [59], and the 10-seater Scylax E10 is expected to fly in 2022 [60].

Figure 6 – Harbour Air electric DHC-2 Beaver.

One of the more successful stories of converting an existing plane to electric propulsion took place in Canada in December 2019 [61]. The airline Harbour Air Seaplanes completed the maiden flight of a DHC-2 Beaver – a seaplane with a capacity of 6 passengers, as seen in Figure 6 [62]. Harbour Air's fleet consists exclusively of seaplanes, all with a low seating capacity and short range [62]. In the event of an emergency, their planes can land anywhere where there is water, which is an advantage considering the narrow criteria for an aircraft to receive approval from authorities to fly commercially. Harbour Air is now in the certification process of the propulsion system for the aircraft [63].

Swedish startup Heart Aerospace is focusing on fully electric nineteen seat passenger planes with their model ES-19, as seen in Figure 7 [64]. Heart Aerospace is aiming for their aircraft to cover transportation between Scandinavian cities before expanding to other destinations. The ES-19 is planned to become certified by 2025 [65].

Figure 7 – Heart Aerospace.

While some manufacturers have their eyes on electric propulsion, others are looking into hybrid electric technologies. California based Ampaire’s Electric EEL in Figure 8 [66] is using a Cessna 337 Skymaster as a demonstrator, and completed their first test flight in 2019 [67]. French manufacturer VoltAero was aiming to convert the same aircraft type to hybrid electric propulsion as well, as their model Cassio (Figure 9 [68]) made a successful test flight in March 2020 [69]. The Electric EEL is equipped with a rear mounted electric motor coupled with a combustion engine on the nose. The Cassio, on the other hand, carries two electric motors on each of its wings and a combustion engine in the aft.

Figure 9 – Ampaire Electric EEL.

Figure 8 – VoltAero Cassio.

As for future hybrid electric aircraft, Airbus, Safran and Daher are currently developing on the EcoPulseTM, scheduled to have its maiden flight in 2022 [70]. The light aircraft is a modified Tecnam P2006T, where 14 electric motors will be mounted on the wings [71]. On the other hand, American startup company Wright Electric is working on developing planes intended for a larger commercial passenger transportation role. The Wright Electric 1 is being conceived to take up to 186 passengers and plans to start flying in 2030 [72].

Figure 10 – Airbus E-Fan X.

One of the better known hybrid electric aircraft projects is the E-Fan X, by Airbus in collaboration with Siemens and Rolls-Royce [73], as seen in Figure 10 [74]. The project is a continuation of the Airbus E-Fan, which holds the accolade as being the electric plane to cross the English Channel in 2015 [75]. The E-Fan X, however, is hybrid-electric and will use a BAe 146 RJ100 as a test bed; a 100-seat short-haul aircraft with four jet engines, where one of the engines will be replaced with an electric motor. The project was originally aiming to start testing by the end of 2020 [76], however the project was discontinued in April 2020 [77].

Seattle startup Zunum Aero is planning to launch a hybrid electric 12 seater. According to different news agencies, the plane was set to complete flight testing in 2019 [78] [79] and begin deliveries in 2022. The plane is said to have been designed to have a range of more than 700 miles and be able to climb up to an altitude of 25 000 feet [80]. The company was reported to be struggling in the summer of 2019 due to financial issues [81], and the current status of the project is, to this day, unknown.

Figure 11 – Project Fresson.

Cranfield Aerospace Solutions (CAeS) in the UK has received a grant from the British Government to convert a Britten-Norman Islander to hybrid electric propulsion, as seen in Figure 11 [82]. The aircraft has a 9 seat configuration and is commonly used for short-haul flights. The project is known as Project Fresson and among its partners are Rolls-Royce, who will be providing the onboard power management system. According to CNN Travel, commercial flights could be available as early as in 2023 [83]. In the future CAeS plans to implement a similar propulsion system to a 19 seat aircraft as well.

Below in Table 2 [32] is a list covering current sustainable aircraft that were found through the literature search. The projects in bold type are the ones mentioned in this section. The abbreviation N/A stands for Not Available, since several projects have not mentioned a date of certification nor when the first flight will take place. The symbol “-“ has been used for projects that have been discontinued.

Table 2 - List over current aircraft projects.

Name	Type	Seats	Country	First flight	Certified by	Source
SkySpark	Hydrogen	1	IT	2007	N/A	[84]
Yuneec E430	Electric	2	CN	2009	2009	[85][86]
Solar Impulse II	Electric	1	CH	2009	2014	[87]
Volocopter Volocity	Electric	2	DE	2011	N/A	[88]
DA36 ESTAR 2	Hybrid Electric	2	AT	2011	N/A	[55]
eHang 184	Electric	1	CN	2015	-	[89]
Elektra Solar OPS One/Two	Electric	1 / 2	DE	2015 / 2011	N/A	[90][91]
Magnus-Siemens eFusion	Electric	2	HU	2016	-	[92]
Hamilton aEro 1	Electric	1	CH	2016	N/A	[93]
HY4	**Hydrogen**	**4**	**DE**	**2016**	**N/A**	[33]
Extra 330LE	**Electric**	**1**	**DE**	**2016**	**N/A**	[56]
Wisk Cora	Electric	2	US	2017	N/A	[94]
eHang 116/216	Electric	1 / 2	CN	2018	2019	[95][96]
Kitty Hawk Flyer	Electric	1	US	2018	N/A	[97][98]
Acubed Vahana	Electric	1	US	2018	N/A	[99]
Bye Aerospace eFlyer 2/ 4	**Electric**	**2 / 4**	**US**	**2018 / 2019**	**N/A**	[58]
Harbour Air DHC-2	**Electric**	**7**	**CA**	**2019**	**2021**	[62]
Ampaire Electric EEL	**Hybrid Electric**	**6**	**US**	**2019**	**2021**	[67]
H55 Bristell Energic	Electyric	2	CH	2019	2021	[100][101]
CityAirbus	Electric	N/A	FR/DE	2019	2023	[102][103]
Aurora PAV	**Electric**	**2**	**US**	**2019**	**2023**	[43][104]
ZeroAvia HyFlyer	**Hydrogen**	**6**	**US**	**2019**	**2023**	[37][105]
XTI TriFan 600	Hybrid Electric	6	US	2019	2024	[51][106]
Lilium Jet	**Electric**	**5**	**DE**	**2019**	**2025**	[49][107]
Kitty Hawk Heavyside	Electric	1	US	2019	N/A	[108][109]
Liaoning Ruixiang RX1E	Electric	4	CN	2019	N/A	[57]
VoltAero Cassio	**Hybrid Electric**	**4-9**	**FR**	**2020**	**2021/2022**	[69][110]

Zunum	**Hybrid Electric**	**12**	**US**	**2020**	**2023**	[111]
NASA X-57 Maxwell	**Electric**	**N/A**	**US**	**2020**	**N/A**	[112]
Airbus E-Fan X	**Hybrid Electric**	**~100**	**FR**	**-**	**-**	[76][73][113]
Autoflight X V600	Electric	2	DE	2022	2025	[114]
Jaunt Air Mobility	**Electric**	**N/A**	**US**	**2022**	**2025**	[44]
Scylax E10	**Electric**	**10**	**DE**	**2022**	**2027**	[60]
EcoPulseTM	Hybrid Electric	N/A	FR	2022	N/A	[70]
Pipistrel Alpha Electro	Electric	2	SI	N/A	2015	[115]
Skai	**Hydrogen**	**5**	**US**	**N/A**	**2020**	[39][38][116]
Eviation Alice	**Electric**	**9**	**IL**	**N/A**	**2021**	[53][54]
Joby Aviation S4	**Electric**	**5**	**US**	**N/A**	**2023**	[42] [117]
Overair butterfly	**Electric**	**4**	**US**	**N/A**	**2023**	[45]
Project Fresson	**Hybrid Electric**	**9**	**UK**	**N/A**	**2023/2024**	[82]
Heart Aerospace ES-19	**Electric**	**19**	**SE**	**N/A**	**2025**	[118]
Wright Electric 1	**Hybrid Electric**	**186**	**US**	**N/A**	**2030**	[72][119][120]
Boeing Sugar Volt	Hybrid Electric	N/A	US	N/A	2030-2050	[121]
Bell Nexus 6HX	**Hybrid Electric**	**4**	**US**	**N/A**	**Mid-2020s**	[46][122]
NASA CHEETA	**Hydrogen**	**N/A**	**US**	**N/A**	**N/A**	[35]
Pipistrel 801 eVTOL	**Electric**	**5**	**SL**	**N/A**	**N/A**	[41]
Airbus/ Audi Pop.Up	Electric	2	FR/DE	N/A	N/A	[123]
EmbraerX DreamMaker	**Electric**	**5**	**BR**	**N/A**	**N/A**	[47]
Dufour aEro 2	Hybrid Electric	2	CH	N/A	N/A	[124]
Volta Voltaré DaVinci	Hybrid Electric	4	US	N/A	N/A	[125]
Elektra Solar Trainer	Electric	2	DE	N/A	N/A	[126]
Breezer/ eCap	Hydrogen	1	DE	N/A	N/A	[127]
Avions Moubossin	Hydrogen	2	FR	N/A	N/A	[128]
NASA STARC-ABL	Turbo electric	N/A	N/A	N/A	N/A	[129]

2.1.3 Challenges

There are challenges that come along with making an aircraft more sustainable, especially connected to electrification. This section will explore the concepts of weight and safety regulations.

Aircraft electrification is challenging the norms of weight and power distribution in terms of design. Current aircraft use engines powered predominantly by petroleum-based fuel, and manufacturers utilise the fact that they are heavier during takeoff than landing to increase their performance and efficiency. In contrast, a battery is relatively heavy and the weight remains constant regardless of its energy content. The energy storage to weight ratio is poor compared to traditional aviation fuels and significantly affects the design, load carrying capacity and range.

The energy density of Jet A-1 fuel is 43 MJ/kg [130], while the energy density of a current rechargeable battery is around 1 MJ/kg [131] (p. 232). Hence, the stored energy weight of a battery is over 40 times greater than of Jet A-1 fuel. If one were to replace fossil fuels with a battery and electric propulsion on an aircraft, it would, without doubt, become heavier. This battery would have to become even larger in order to compensate for the excess weight, which would just result in even more weight being added to the aircraft.

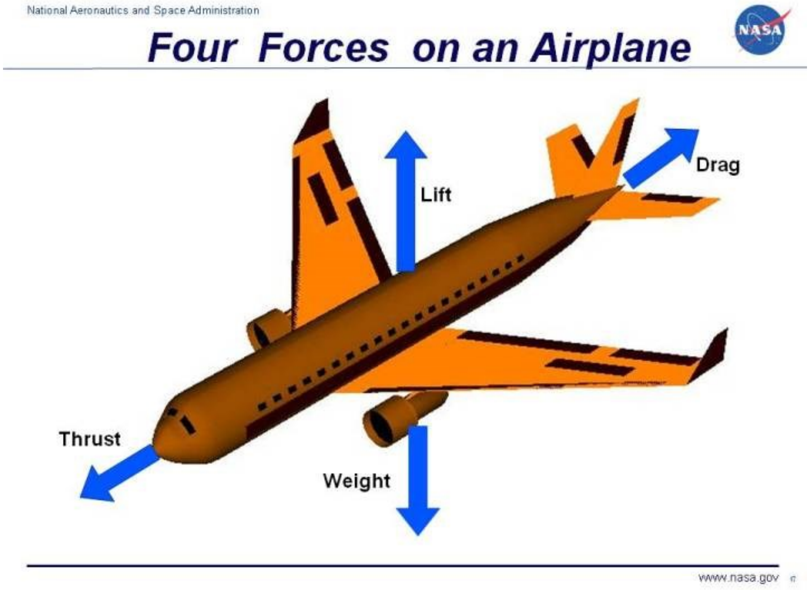


Figure 12 – Forces on an airplane.

Figure 12 [132] shows the forces acting on an aircraft when flying. A plane attains steady level flight when the force of lift equals to the force due to gravity, g, acting on an aircraft of mass, m_{plane}. This is a vertically downward weight vector as shown, which equates to the mass of the plane multiplied by gravity.

$$F_{lift} = F_{gravity} = m_{plane} \times g \tag{1}$$

When the weight is increased, the lift also needs to be increased. In order to do this, more power is required, and therefore more battery capacity, which increases the weight again.

The Work-Energy Theorem states that the Work (W) is equal to the distance over which a force acts (Δx) multiplied by force (F), hence

$$W = F \times \Delta x \tag{2}$$

Power (P) is work divided by time (t)

$$P = \frac{W}{t} \tag{3}$$

Equation (2) is inserted into (3), hence

$$P = F \times \frac{\Delta x}{t} = F \times \Delta v_z \tag{4}$$

Δv_z is equal to the downward velocity of air that the aircraft pushes downward.

Equation (1) is inserted into equation (4), hence

$$P = m_{plane} \times g \times \Delta v_z \tag{5}$$

The lift that an airplane provides is equal to the rate which it delivers downward momentum to the air it displaces. This means that the force of gravity must be equal in magnitude to the downward magnitude of the deflected air multiplied by the rate at which air gets deflected, hence

$$F_{lift} = m_{plane} \times g = \dot{m}_{air} \times \Delta v_z \tag{6}$$

$\dot{m}_{air}$ is equal to the mass flow rate.

The mass of the air that the plane affects is the volume of the cylinder that it sweeps out multiplied with the density of the air, ρ_{air}. This relevant cross-sectional area will be called A_{sweep} and the volume it sweeps out per unit time is $A_{sweep} \times v_{flight}$. Therefore, the mass flow rate is equal to

$$\dot{m}_{air} = \rho_{air} \times A_{sweep} \times v_{flight} \tag{7}$$

Now, the only outstanding quantity that is unknown is the area of air affected by the plane, A_{sweep}. This is not the cross-sectional area of the plane but rather the area of influence the plane has on the surrounding air. This changes with the relative velocity of the plane of the air around it. At cruising speed, the plane dissipates vortices that have roughly the radius of the length L of the plane's wings. This circle is approximated as a square. The relevant area is therefore

$$A_{sweep} = L^2 \text{ at cruising speed} \tag{8}$$

Equation (8) is inserted into equation (6)

$$F_{lift} = \Delta v_z \times \rho_{air} \times L^2 \times v_{flight} \tag{9}$$

Equation (9) shows the force that the lift needs to provide, and so the aircraft is sweeping out a tube of air and shifting it downwards so that downward acceleration of air is equal to the downward pull of gravity on the aircraft. To sum up, the aircraft avoids falling by streaming momentum downwards by using the air. By rearranging equation (9), it can now be solved for Δv_z

$$\Delta v_z = \frac{F_{lift}}{\rho_{air}\times L^2 \times v_{flight}} = \frac{m_{plane}\times g}{\rho_{air}\times L^2 \times v_{flight}} \tag{10}$$

Equation (10) is inserted into equation (5)

$$P = m_{plane} \times g \times \frac{m_{plane}\times g}{\rho_{air}\times L^2 \times v_{flight}} = \frac{m_{plane}^2\times g^2}{\rho_{air}\times L^2 \times v_{flight}} \tag{11}$$

With this equation, it is easier to identify what variables really impact the energy requirements of the aircraft. Notice that as the plane flies faster, the power drawn by the engine becomes smaller, but this equation neglects to consider drag. The total power needed to fly is minimised when the force of lift and the force of drag become equal, as in equation (1). Therefore, the power requirement needs to become doubled in order to get the total power requirement at cruising speed, hence

$$P = \frac{2 \times m_{plane}^2 \times g^2}{\rho_{air} \times L^2 \times v_{flight}} \tag{12}$$

Equation (12) reflects why increasing the mass is such a big issue. The mass component of the equation is not only squared but also doubled. Doubling the mass will increase the power requirements 8 times. Current batteries cannot deliver sufficient energy that is needed for a long flight. It is also worth noting that electric motors are smaller and lighter than a conventional engine, but the battery weight currently negates this advantage. An all-electric aircraft might have to adjust to the excess weight by reducing its range or seating capacity.

Safety is of high priority in civil aviation, and has its levels of governance from global, to regional, to national level. ICAO is an agency of the UN responsible for setting international standards and regulations to ensure a safe and sustainable civil aviation sector [133]. EASA is an agency of the EU (the European Union) and is responsible for aviation safety in the EU, Switzerland, Norway, Iceland and Lichtenstein, thus a regional authority [134]. In Norway, the Aviation Act (Luftfartsloven) [135] is administered by the Ministry of Transport and delegated to the national CAA (Civil Aviation Authority) [136]. Both the Ministry of Transport and the CAA are members of EASA and ICAO.

A Norwegian manufacturer would have to apply to EASA in order to get certified [137]. A new aircraft would need to comply with EASA's regulations, and pass multiple tests both on the ground and in flight. Aircraft manufacturers have to verify that all components of the aircraft are safe for operation, down to the centimeter. Moreover, the aircraft have to pass several stages of testing and demonstrations. As EASA describes, the first stage starts with the introduction of the project by the aircraft manufacturer, and the authorities set up a team and a set of rules for the development. The team needs to agree on how the compliance of the aircraft is going to be demonstrated. Aircraft manufacturers must demonstrate the compliance of the structure, engines, electrical systems, flight control systems and the flight performance. This step is the longest compliance process and is set to 5 years for larger aircraft and can be extended. When the aircraft does satisfy the given requirements, EASA will issue the certificate. This certificate is parallel for operation to other airspaces, such as the US, Canada, etc. [137].

For aircraft with alternative sustainable propulsion systems, the process is likely to take multiple years. Critical components onboard can be batteries or hydrogen, which will be further explored in Section *2.2 Energy Storage*. As seen in the Section *2.1.2 Current projects*, many of the examples are using an existing and already certified aircraft as a testbed. It is more likely for these projects to become certified faster than the projects with aircraft built from scratch.

2.1.4 Advantages

As stated in the introduction to this work, a lower environmental impact is a key advantage to make aviation more sustainable. Noise reduction and lower operating costs are other additional benefits.

Aviation accounted for 2 % of the global CO_2 emissions in 2017, and is not likely to decrease in the near future due to flight demand and population growth. There is no doubt that CO_2 emissions have an environmental impact, but effects from other GHGs also need to be taken into consideration. During a flight, an aircraft emits soot particles and gasses such as NO_x, hydrocarbons, CO and SO_x, which are identified to potentially be affecting the climate [138]. With zero emission propulsion systems, the GHG emissions from a flight could be abolished entirely. A hybrid electric solution would contribute to a reduction, and mixing biofuels would lead to a more carbon neutral flight. These technologies would also result in an overall improvement in the air quality in communities close to larger airports. Noise is the most noticeable impact that an aircraft can have on its close surroundings [139]. The replacement of engines with electric motors would lead to noise reductions for both people who work in the aviation sector, passengers and nearby local communities.

As seen in Section *2.1.2 Current projects*, range and seating capacity seem to be restricting factors for aircraft set to fly within the next five years. It is, therefore, more likely that shorter routes will be subject to replacement by alternative sustainable propulsion. These aircraft could potentially replace short commercial flights currently operated by smaller turboprop engine aircraft or flights for private purposes. The independency from fossil fuels could result in lower operating costs due to the operator not having to pay for the fuel. This would, in theory, also mean that the operator would not be subject to pay the air passenger tax, which in Norway, among many countries, have implemented as an offset to the environmental impact of a flight [140].

2.2 Energy Storage

Section 2.2 will explore different types of sustainable energy storage methods. Included here are those believed to be the most prominent technologies. Energy storage technologies that are not mentioned in this section will be discussed in Chapter *5. Discussion*.

2.2.1 Batteries

Batteries are used to store chemical energy and convert it to electrical energy when needed, as they utilise the electric potential from two different materials to create voltage. This is due to the difference in charge between the two electrodes: the anode and cathode. The anode is an element located on the left side of the periodic table with few valence electrons. The cathode consists of elements, often a metal located on the right side of the periodic table, which has a fuller valence shell. Additionally, a battery consists of an electrolyte, is a solution that contains free ions and is electrically conductive.

As previously mentioned, Jet A-1 fuel has 43.02 MJ/kg in specific energy [130]. In order to make a comparison with battery storage in terms of specific energy density, aviation fuel can be seen to have an energy density of 11.67 kWh/kg. This should be compared with lithium-ion batteries commonly used in EVs such as a Tesla Model 3, which have a specific energy of 250 Wh/kg [141].

Some of the applications of batteries in present day commercial aircraft are in cockpit voice recorders, flight data recorders, emergency lightning, main batteries for standard and emergency power, auxiliary power units (APU) or main starting batteries, and special functions such as torches (flashlights) and emergency equipment.

The most widely used battery chemistries today are zinc-carbon, lead-acid, alkaline, and lithium batteries. Lithium accounts for most of today's battery applications due to its high energy density and developed technology status. In the aviation sector nickel-cadmium (NiCd) batteries are commonly used as the main battery for larger commercial aircraft, while most small aircraft use lead-acid batteries. In 2013 the battery technology for the aviation industry reached a milestone as the Boeing 787 Dreamliner was the first larger aircraft to use lithium-ion batteries (LIB). Unfortunately, the aircraft had several issues in the beginning due to *Thermal Runaway* [142]. As a result of the problems with the Dreamliner, the competing aircraft manufacturer Airbus decided to keep the NiCd batteries for their new model Airbus A350 XWB, released two years later in 2015 [143].

Thermal runaway is when an internal source of heat leads to an increase in temperature. For a battery, this can lead to an ignition, which can further result in an explosion. Liquid batteries such as NiCd and LIB are prone to this issue, unlike solid-state batteries (SSB), where the flammable liquid electrolyte is replaced with a solid material.

Lithium-ion batteries

The LIB revolutionised battery technology with its high energy density and potential for higher capacity and lifetime. LIB had at the end of 2019 a practical energy density of between 100-265 Wh/kg, which is twice as high as the energy density of a standard NiCd battery [144] [145]. Generally, LIBs have a practical higher energy per unit weight and also per unit volume, and failure often leads to thermal runaway. LIB can utilise different materials as a cathode, which is one of the reasons for its high capacity. The most common combination is a graphite anode and a lithium cobalt oxide ($LiCoO_2$) cathode. Other cathode materials are lithium ion manganese oxide ($LiMnO_2$) and lithium iron phosphate ($LiFePO_4$) [145]. Another combination with nickel, manganese, and cobalt (NiCoMn, also known as NMC811) is one of the more optimal cathode-combinations for a LIB as for now. With a liquid electrolyte, the battery has a specific energy density of 255 Wh/kg. Yet, it can reach a density as high as 495 Wh/kg if the liquid electrolyte is replaced with a solid variant [146]. Battery manufactures, and researchers are aiming to reduce the amount of cobalt for EV batteries in general, considering the ethical dilemma of cobalt extraction, which will be discussed later in this section under *Reserves and recycling* [147].

Table 3 shows an overview over different LIBs.

Table 3 – Lithium-ion batteries.

Type	**Specific energy (Wh/kg)**	**Cycle life**	**Reference**
Lithium cobalt oxide ($LiCoO_2$)	150 – 240	500 – 1000	[148] [149]
Lithium nickel manganese cobalt oxide ($LiNiCoMnO_2$)	255 – 495*	Unknown	[146]
Lithium ion manganese oxide ($LiMnO_2$)	100 – 150	300 – 700	[148]
Lithium iron phosphate ($LiFePO_4$)	90 – 120	2000 +	[148]

**A solid electrolyte-variant can reach up to 495 Wh/kg*

Lithium Solid-State batteries

In solid-state batteries (SSB), the electrolyte, which generally consists of a liquid substance, is replaced with a solid material. The solid electrolyte developed is often made out of a glass and ceramic material, where the cathode still can be lithium based. SSBs today are of small sizes and are therefore used in small devices, such as pacemakers and RFID-components.

In 2017 Professor John Goodenough and his team of engineers in the *Cockrell School of Engineering* at *The University of Texas at Austin* developed the first SSB, which was allegedly longer-lasting and safer to use than the traditional LIBs. This new design could operate at temperatures as low as -60 °C and had three times higher specific energy density compared with traditional LIBs. This SSB had a lower environmental impact due to it consisting of more abundant resources. The study focused on using a Li^+ and Na^+ glass electrolyte, and an alkali metal as an anode [150].

As mentioned earlier in this section, a NMC811combination can be designed as a SSB, and are included in Table 4.

Table 4 – Solid State Batteries.

Type	Specific energy (Wh/kg)	Cycle life	Reference
Lithium catode, glass-electrolyte, alkali metal as anode	400 ~ 750*	23 000	[150] [151]
Lithium nickel manganese cobalt oxide ($LiNiCoMnO_2$)	495	3000 – 4000 **	[152] [146]

Assumption from the study Alternative strategy for a safe [150]* [153] * Depends of metal combination ratio*

Replacing the electrolyte with a solid state material allows one to use a pure lithium cathode instead of employing a mix of lithium with graphite and/or cobalt [154].

Lithium-sulphur and Lithium-nickel batteries

The lithium-sulphur (LiS) combination is another promising battery technology with its high theoretical specific energy of 3 730 Wh/kg. LiS has an open-circuit voltage of 2.23 V with a specific capacity of 1675 mAh/g [155]. Several types of LiS batteries are currently being researched and can also be found as SSBs. A study published in the journal *Frontiers in Energy Research* describes the possibilities of the first LiS battery packs. The study concludes that the first battery packs would last ≥ 100 cycles and hold ≥ 400 Wh/kg energy density. [156]

The most efficient LiS-battery was developed by scientists at Monash University in Australia in January 2020. The research stated that the technology is close to commercialisation [157], and claimed that one charge could give an EV enough energy to last more than 1 000 km. Another key finding was that the theoretical energy density for present LiS batteries is 2 500 Wh/kg, compared to LIB with a theoretical density of 500 Wh/kg; Meaning that LiS batteries are significantly lighter. Sulphur is an abundant material and therefore expected to have a lower cost of production as soon the technology is commercially available. [158].

Meanwhile, the first LiS battery packs are initially designed to last ≥ 200 cycles and hold ≥ 400 Wh/kg energy density [156].

Table 5 – LiS and LiNi batteries.

Type	Specific energy (Wh/kg)	Energy density (Wh/l)	Cycle life	Reference
Lithium –sulphur (LiS)	500 | < 2 510*	Unknown	≥ 200	[156]
Lithium – nickel (LiNi)	500	1 000	≥ 450	[159] [160]

**Theoretical*

Sion Power is also associated devoting resources towards LiS battery technology. Substantial rounds of testing concluded that the cycle life of LiS-batteries was not sufficient for an EV. Due to this discovery, the company focused on a new type of LIB based on a nickel-rich cathode. By the end of 2018, Sion Power claimed to have developed a "superlight" lithium-nickel (LiNi) battery, with an energy density of 500 Wh/kg, 1000 Wh/l, and cycle life of at least 450-500 charges [159] [160]. The battery has been demonstrated in the laboratory and can reach a practical energy density of 700 Wh/kg. Sion Power has yet to announce when these batteries will be available for the commercial market.

Lithium-air batteries

Lithium-air (LiO_2) batteries have a theoretical energy density of 11 430 Wh/kg, which is close to the energy stored in aviation fuel. The calculations of the energy density are based on lithium atoms in a charged state. As the cell discharges, oxygen from the surrounding air enters the cathode, which results in a mass expansion. With the mass of air included, the theoretical specific energy capacity is 3 458 Wh/kg [161]. LiO_2 batteries have yet to be developed and manufactured, and therefore the practical energy density is difficult to estimate. A problem with LiO_2 batteries is the difference in charge to discharge voltage. The battery needs approximately twice the voltage for charging as for discharging, which leads to a reduced battery efficiency [162].

Another issue is the limited lifetime cycle for LiO_2 batteries. Since the idea is to use air as cathode lithium will, in a similar way, react with other air-chemicals such as nitrogen, water, and carbon dioxide. A study published in 2018 stated that it could be a simple issue to solve. The project was done by academics and the Argonne National Lab [163]. Thin air with low oxygen levels at high altitudes can be a challenge to implement this technology in aviation.

Table 6 – Lithium-air battery.

Type	Specific energy (Wh/kg)	Cycle life	Reference
Lithium-air (LiO_2)	11 430*	100 – 700 +	[163]

**Theoretical. Excludes air incoming under discharge process*

Silicon-air batteries

The silicon-air battery (SiO_2) is yet another alternative type of battery. It has a high energy density and is advantageous, considering that silicone is a non-toxic and abundant element [164]. There are many types of SiO_2 batteries, however, the development is at an early stage.

Table 7 – Silicon-Air battery.

Type	Specific energy (Wh/kg)	Energy density (Wh/l)	Reference
Silicon-air (SiO_2)	8 470*	21 090*	[165]

**Theoretical*

Aluminium-ion and aluminium-air batteries

The aluminium-ion (Al-ion) battery utilises pure aluminium metal as anode coupled with varying cathode metals. It has a practical energy density of up to 200 Wh/kg and a theoretical energy density of 1090 Wh/kg. In 2014, battery system manufacturer Phinenergy created an EV equipped with a combination of AlO_2 and LIB. The vehicle had a specific energy density of around 250 – 400 Wh/kg. Two years later, an SSB-fibre shaped aliminium-air (AlO_2) battery with a specific energy of 1 168 Wh/kg was made [166].

Table 8 – Aliminium-ion and aluminium-air batteries.

Type	Specific energy (Wh/kg)	Reference
Aluminium-ion (Al-ion)	200 (1090*)	[166]
Aluminium-air (AlO_2) and combined LIB	250 – 400 (1 168*)	[166]

**Theoretical*

Zinc-ion battery

There are varieties of zinc-ion batteries. Recent studies have confirmed that these batteries paired with a liquid electrolyte can have a specific energy density as high as 400 Wh/kg and up to 500 Wh/kg with the employment of a solid state electrolyte.

The solid state zinc-ion battery has a favorable capacity and a high cycle life, with as much as 80 % of its capacity remaining after 1000 cycles and no traces of dendrites on the zink anode. This reduces the chances of thermal runaway [167] [168].

Table 9 – Zinc-Ion battery.

Type of lithium battery	**Specific energy (Wh/kg)**	**Cycle life**	**Reference**
Zinc-ion	400 – 500	> 1000	[167] [168]

Reserves and recycling

The total reserves of Lithium were 13 919 Mtonnes in 2018, with the largest reserves located in Australia, Chile, China, and Argentina [169]. Lithium does not occur in a pure form in nature, as it is usually chemically bounded to other mineral elements. [170]. It is questionable if the amount of lithium resources is adequate to sustain a possible electrification of the aviation industry in the coming years. The industry might need to look for other key materials.

There is little information about battery recycling that the authors could find, however, one source claims that more than 66 % of LIBs can potentially be recycled in China, home to one of the world's largest global battery material industries, by 2025. It is also estimated that the same year 76 % of all cobalt used in batteries can be recycled [171]. The process of extracting cobalt from nature involves mining. The Democratic Republic of Congo is home to over half of the world's cobalt reserves [169] (p. 29), and the extraction has been linked to inhumane conditions, such as child labour, on multiple occasions [172].

Other vital materials for batteries, such as silicone and sulphur, are both abundant materials. About 27 % and 0.05 % of the earth's crust consists of silicone and sulphur respectively [173] [174]. Zinc is the 23rd most abundant metal and can be found in soil, air and water [175]. Aluminium is, likewise, an abundant material [176].

Many manufacturers of EVs operate with a battery warranty of approximately 70 - 80 % of the remaining capacity, eight years or 160 000 km [177]. Worn out cells can be replaced. Outdated batteries that still have a capacity remaining that can be used as energy storage for private households in order to maintain the capacity on public power grids without a heavy investment in high grid capacities; to keep electricity prices down [178].

The lithium amount can be critical for the electrification of road, marine and aerial vehicles, and electronics. A circular economy is an essential practice in avoiding an overexploitation of rare minerals and to secure sufficient key minerals such as lithium.

2.2.2 Hydrogen

Hydrogen is often found chemically bound to oxygen as water molecules in nature, but it also forms chemical compounds with most other elements due to its low atomic weight. Furthermore, hydrogen is the most abundant element in the universe [179], and can therefore be produced from different sources in various ways. This section will further explore hydrogen as an alternative to sustainable propulsion. Hydrogen is an energy carrier because it is produced from an energy source [180]. The process of transforming an energy source to a carrier will require energy, which is released when the energy carrier is used. One can utilise this for transportation to specific places for different purposes, such as one can do with gasoline, diesel, and hydrogen, as opposed to energy sources that can neither be stored nor controlled, such as wind and solar power. Hydrogen has a specific energy density of 119.96 MJ/kg which is almost three times the amount of the energy density in Jet A-1 fuel.

Storage

Additionally, hydrogen can be stored in a variety of forms; Compressed Gaseous Hydrogen (CGH_2), Liquid Hydrogen (LH_2), ammonia, Liquid Organic Hydrogen Carriers (LOHC) and metal hydrides [181] (p. 31-32).

CGH_2 and LH_2 are both storage methods where the natural state of hydrogen under different conditions is taken advantage of. The gravimetric density of CGH_2 is 20 kg/m^3 at the pressure of 300 bar. By further compression to 700 bar, the gravimetric density lies at around 40 kg/m^3 [181] (p. 31), and hence there is not a linear relationship between the energy density and pressure. For storing CGH_2, robust tanks are needed in order to withstand the high pressure, such as steel or composite cylinders [182]. Most hydrogen vehicles are equipped with CGH_2 tanks, and therefore the tank to hydrogen weight ratio is individual for the respective vehicle. 700 bar storage tanks are the preferred option for cars, while buses and other larger vehicles often accommodate a 350 bar storage tank. The CEO of ZeroAvia, Val Miftakhov, stated in an interview in February 2020 that 12 kg of a 350 bar storage tank is needed for every 1 kg of hydrogen, and that 16 kg of a 700 bar storage tank is needed for every 1 kg of hydrogen [183]. This would mean a hydrogen to tank weight ratio of 8 % and 6 % respectively. Tank manufacturer Hexagon Lincoln also confirms these weight percent estimates through their product range of CGH_2 tanks [184].

For liquefaction, the hydrogen gas has to be cooled down to -253 °C (20 K) at athmospheric pressure. The gravimetric density of LH_2 is 71 kg/m^3 [181] (p. 31). There are not many producers of LH_2 today, and only a few demonstrated projects where LH_2 has been used in a vehicle [182] (p. 27). Generally, its technology status is not at a mature stage. The temperature for liquefaction is relatively close to the absolute zero (0 K) on the thermodynamic temperature scale, and cryogenic tanks are needed to maintain the temperature. There are a few suppliers of LH_2 tanks, but no specific estimates are found for the tank to hydrogen weight ratio.

Ammonia, LOHC and metal hydrides are methods where another material or compound is used for the purpose of storage. Hydrogen stored in ammonia has a gravimetric density of around 121 kg/m^3. LOHC are hydrocarbons which can be increased to a higher capacity of hydrogen absorption, where the gravimetric density can vary depending on the chemical compound [181] (p. 32). Metal hydrides are a method where hydrogen diffuses to the surface of a solid state metal and then forms interstitial compounds [185] (p. 24). Most of the material based sorage methods are still in development. There will be a need for additional applications in order to extract the pure hydrogen from the storage methods mentioned, which on an aircraft would take up additional space and energy. They will therefore not be explored further in this project.

Fuel Cells

A fuel cell transforms chemical energy stored in a fuel, such as hydrogen, to electrical energy. Using a hydrogen powered fuel cell for propulsion will have a low environmental impact and a high efficiency [186]. A fuel cell consists of a cathode and an anode side separated by a membrane, which only allows protons to pass through. On the anode side, there is a catalyst that separates the hydrogen atoms into electrons and protons. Protons diffuse through the membrane, while electrons pass through an external circuit to produce an electric current. The electrons pass around the membrane and to the cathode side, where they react with the protons and oxygen, forming water. A fuel cell produces electricity with a voltage of 0.7 V. If a higher voltage is desired, then several unit cells can be combined into stacks. Everything that is needed to operate and produce electrical energy for the fuel cell is referred to as the Balance of Plant (BoP). The BoP includes elements such as processor, humidification management, thermal management, interface functions, and electric power conditioning [187] (p. 2).

Fuel cells are classified by their type of electrolyte. There are several different types of fuel cells, but the two most developed are Proton Exchange Membrane Fuel Cell (PEMFC) and Solid Oxide Fuel Cell (SOFC). Development and research have been concentrated around these two types of fuel cells for aircraft applications, and they are currently used in vehicles and power stations. Other fuel cells are Alkaline Fuel Cells (AFC), Phosphoric Acid Fuel Cell (PAFC), and Molten Carbonate Fuel Cell (MCFC) [185] (p. 32-33). AFC was the first fuel cell to be invented, PAFC is a type of fuel cell that requires space, complicated handling of water and a relatively low electrical energy efficiency and is, therefore, better suited for fixed applications. MCFC operates at a high temperature, which allows the utilisation of hydrogen-containing gases. Just like PAFC, the MCFC requires a lot of space [188].

The PEMFC uses pure hydrogen as fuel and is suitable for stationary, portable and automotive applications [189]. The use of PEMFCs in hydrogen vehicles has led to technological advancement for this type of fuel cell [187]. The PEMFC is a low temperature fuel cell, with an operating temperature between 50 - 90 ºC. Further, it has a short startup time and does not require a lot of extra equipment to maintain the operational temperature. The PEMFC uses a polymer membrane as an electrolyte and takes up little volume. The metal platinum is used as a catalyst. Over time, the platinum becomes destroyed by sulphur and carbon monoxide, which increases the operational cost. The PEMFC must be operated under conditions where water is in a liquid state since the solid polymer membrane must be hydrated in order to allow for proton diffusion [187]. With current PEMFC technology, the humidity in the fuel cell must be above 80 % to prevent proton conductivity inhibition and excess drying. The humidity also needs to be below 100 % to prevent liquid water from amassing in the electrodes [190]. The BoP requirements are affected by the amount of heat generated by the fuel cell and the required removal method. A PEMFC stack can be cooled with reactant airflow if the stack is smaller than 100 W. A stack between 100 W and 1kW needs a separate air-cooling system. The system needs pumps for cooling and air blowers. A water-cooling system is required when the stack is higher than 1 kW. The BoP for the fuel cell will, therefore, be significantly increased when a separated cooling system is added. A PEMFC system has an efficiency between 20 and 60 %, but the maximum theoretical efficiency is 83 % when H_2 is used as fuel [190].

SOFC is a type of fuel cell with high electrical and energy efficiency. SOFC is different from the PEMFC in several ways. The operating temperature is between 500 °C and 1000 °C, and this results in a slow startup time [187]. The electrolyte is made of a ceramic material, and the fuel cell does not require the use of pure hydrogen. Instead, one can use other fuels consisting of hydrocarbons; however CO_2 will come out as a waste product. The efficiency of a SOFC ranges from 40 to 65 %, but the efficiency has the potential to be higher than 85 % with combined power and heat applications. After PEMFC, SOFC is the second most used fuel cell worldwide because it is easily applicable to both smaller and larger power supplies [191].

There are advantages and disadvantages to the PEMFC and SOFC fuel cell types, such as operating temperature, type of fuel required and the weight of the necessary BoP. A PEMFC is better fitted in an aircraft rather than a SOFC fuel cell. This is due to the lower operating temperatures of PEMFCs and the corresponding smaller BoP requirements [187]. There are still challenges with incorporating fuel cells as a power source on an aircraft, but with some technology improvement the potential reduction in CO_2 emissions is a substantial advantage.

Hydrogen Powertrains

A hydrogen fuel cell powertrain allegedly has a four times higher energy density than the most durable electric batteries available today [192]. By converting chemical energy directly to electrical power, fuel cells are more efficient compared to the internal combustion engine, where chemical potential energy is converted to thermal energy and then to mechanical work [193]. Inside a hydrogen vehicle, the powertrain generally consists of a hydrogen storage, fuel cell stacks accompanied by its BoP and a battery. Hence, a hydrogen vehicle with such a powertrain configuration is technically a hybrid electric vehicle.

It is also feasible to utilise H_2 as fuel for a gas turbine. This was the case for the Tu-155 as mentioned in Section 2.1.1. Mixing H_2 with, for example, natural gas is also beneficial for reducing the emissions from the cumbustion process. However, there are challenges with this technology, such as its high reactivity and increased flame speed, that requires further research. Therefore, this type of hydrogen propulsion will not be further explored in this thesis [194] (p. 8).

There is a handful of aircraft that utilise hydrogen propulsion, as mentioned in Section *2.1.2 Current Projects*. As an example, ZeroAvia has already converted a Piper-M Class for demonstration. The powertrain in the aircraft uses CGH_2 and a PEMFC, and requires at least 250 - 300 kW of power [195]. The company's ultimate goal for the future is a 19 seater with a range of 500 miles. Where the tanks for the hydrogen will be located will depend on the airframe employed. Unless it is possible to integrate them, the tanks may be attached externally on the wings or fuselage. ZeroAvia is generally aiming to use CGH_2 storage instead of LH_2 for a simpler certification process, since a LH_2 system will require added components [195]. However, ZeroAvia believes that LH_2 eventually will be needed for larger aircraft with a longer range due its higher energy density. Figure 13 [37] shows ZeroAvia's vision where the hydrogen value chain and a possible future powertrain configuration is displayed. They envisage the hydrogen produced from a renewable energy source in order to achieve sustainable propulsion.

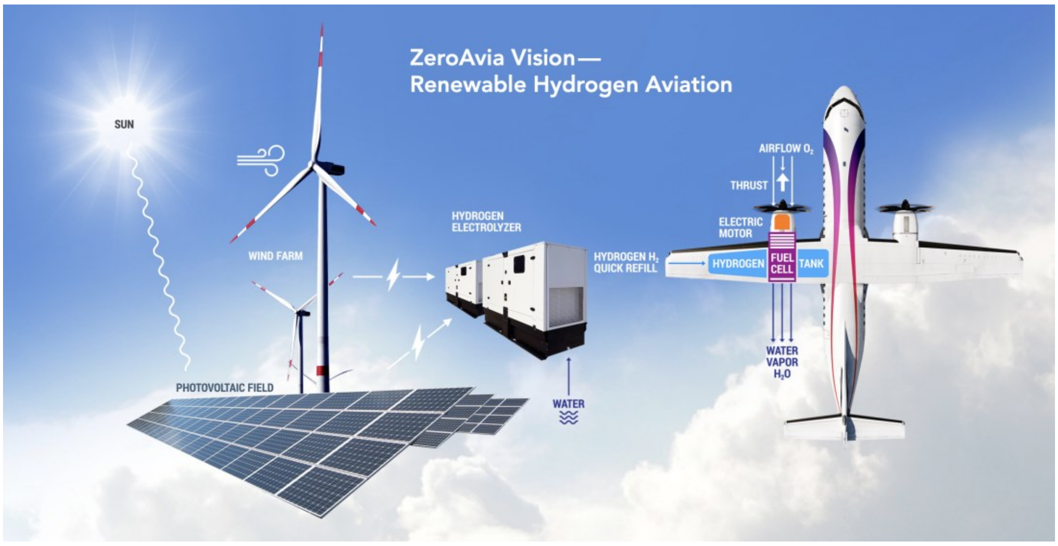


Figure 13 – Hydrogen system in an aircraft.

Hydrogen powertrains have been integrated into smaller aircraft as well, such as the previously mentioned HY4. The four seat aircraft accommodates a CGH_2 tank and battery which are placed in each of its respective hulls. The electric motor and low temperature fuel cell stacks are located inside a nacelle mounted between the two fuselages [34]. The HY4 is a modification of the Pipistrel Taurus G4 which again is based on Pipistrel's self launching glider Taurus Electro [30]. One advantage with converting a self launching glider to hydrogen propulsion is that the propulsion system is only needed for takeoff and climb. One does not have to rely on any form of propulsion once up in the air, as gliders are made for just that. It follows that the certification process of an aircraft of this type would be simpler, as opposed to any aircraft similar to ZeroAvia's retrofitted Piper M-Class – Set aside that the HY4 was strictly a test project.

Environmental impact and challenges

The direct emissions from a fuel cell are water and heat, which is advantageous compared to the greenhouse gases from the internal combustion engine. Hydrogen production can be environmentally friendly if produced through electrolysis, with electricity from a renewable power source such as wind energy or hydropower. Thus its name, green hydrogen [196]. Other production methods such as steam methane reforming, partial oxidation, and autothermal reforming of hydrocarbons emit CO_2. However, the CO_2 from these production methods can be captured and either stored or utilised. This is called blue hydrogen and is also considered environmentally friendly due to no direct emissions of GHGs [196]. Blue and green hydrogen is a good alternative energy source as opposed to aviation fuel when considering GHG emissions. One of the most significant drawbacks of hydrogen is safety and limited technological availability. Hydrogen is flammable by concentrations of 4-75 % in the air [181] (p. 34). Hydrogen propulsion systems in vehicles are not very common, although there are a few car models currently available commercially [197]. Today, hydrogen is commonly used in oil refineries and for methanol and ammonia production [185] (p. 29-30). Thus, there is an existing infrastructure to produce and transport pure hydrogen to a limited degree.

2.2.3 Biofuel

Biofuels are a collective term for fuels made from biological material and can occur as both liquid and gas. Replacing fossil fuels with biofuels on an aircraft can compensate for GHG emissions as long as one restores the equivalent amount of biomass extracted. This is due to the

CO_2 released into the atmosphere during combustion is offset by the CO_2 captured throughout the plant's life. Additionally, no CO_2 should be emitted into the atmosphere when harvesting the biomass. It is common to distinguish between 1st and 2nd generation biofuels by the raw material used and production method. *1st generation biofuels* are produced from raw materials which can also be used to create food or animal feed, such as oily seeds or sugar [198]. Biofuels such as biodiesel and bioethanol fall into this category. *2nd generation biofuels* are produced from all types of biomass such as residues and waste from forestry or agricultural industry [199].

Different types of biofuels can replace or be mixed with fossil fuel, and the latter is of common practice in Norway today. Biofuels that can be mixed into gasoline are bio-naphtha and bioethanol. Bioethanol is produced through fermentation of plants that contain starches and sugars, such as corn, sugar cane and wheat. Diesel can be combined with biodiesel types such as FAME (Fatty Acid Methyl Ester) and HEFA (Hydrotreated Esters and Fatty Acids). Biodiesel and bio-naphtha are made from vegetable or animal oils such as canola and palm oil [199].

Using biofuels require no alterations in distribution systems and aircraft engines, and can be directly combined with fossil fuel. This means that biofuels can be filled directly to existing aircraft, however, there is a current limit to a maximum of 50 % mix into aviation fuel [200]. Biofuels have therefore the potential to become more widespread and hold a larger share of the jetfuel market in the near future.

A long-term approval processes along with a series of comprehensive tests are required for new types of jetfuel to become certified for operation. Biofuels were first certified for the aviation industry in 2009. Subsequently, several production methods have been approved, and aviation biofuel can in theory be produced from almost any type of biomass. Both in Norway and internationally, a growing number of flights using jet biofuel have taken place over the course of the past 10 years. The airlines Norwegian Air Shuttle and SAS (Scandinavian Airlines System) both conducted their first flights using jet biofuels in 2014 [200]. SAS use HEFA made from a variety of fats and vegetable oils, and has strict criterias for the jet biofuels they use; "The biofuel used should be produced from used raw materials that require as little land as possible and that do not affect the availability of plants used in food production or drinking water in production, and which have a positive impact on biodiversity. SAS does not approve waste from palm oil production as a commodity." [201]

From 2020 the Norwegian government has set a requirement that all aviation fuel sold in Norway should have a 0.5 % proportion of advanced, 2^{nd} generation biofuels. The ultimate goal is that, by 2030, 30 % of the aviation fuel sold in Norway should originate from biofuels [202]. In addition, problematic raw materials, such as palm oil, shall not be used. With this, Norway will be the first country in the world with a biofuel requirement for aviation, and "according to the Norwegian Environmental Agency, this will result in a reduction in global GHG emissions of 14 000 tonnes of CO_2 equivalents in the first year." [202] Oslo airport has offered jet biofuel through the central tanking facilities at the airport since January 2016 [200].

The production of fuel from biomass is limited, although the demand for jet biofuel is increasing and there is a growing amount of investments in the production capacity in various parts of the world [200]. Another challenge with the global production of bioethanol and biodiesel is that the crops can occupy carbon-rich land areas or farmland that is critical for food supply. In order to ensure this, the EU has implemented their sustainability criteria for biofuels, where thorough documentation is required for a biofuel producer to become certified [203]. In Norway, there is a higher potential to produce biofuels from forestry instead of agriculture. The global supply of biofuels is currently scarce compared to the production of gasoline and diesel. Biofuels have therefore a higher price and a smaller, but growing, market, but a beneficial technological availability.

2.3 Sustainable propulsion systems

This thesis will focus on three main areas concerning sustainable propulsion system; all-electric propulsion, hybrid electric propulsion and turbo electric propulsion. Aircraft can be categorised by the degree of hybridisation of their power and energy sources. H_P and H_E, in this thesis, are the definitions of hybridisation concerning power and energy (Table 10) [204]. The endpoint values of H_P and H_E are given by $0 \leq H_P \leq 1$ and $0 \leq H_E \leq 1$.

Table 10 – Classification of propulsion architectures.

System	H_P	H_E
Conventional	0	0
All-electric	1	1
Parallel Hybrid	< 1	< 1
Serial Hybrid	1	< 1
Turboelectric	> 0	0

An all-electric aircraft uses only electric power for propulsion ($H_P = 1$, $H_E = 1$), as seen in Figure 14 [204]. The aircraft requires a battery storage with enough energy to operate the electric motor. The advantages of all-electric propulsion systems are the overall efficiency of more than 90 % and nearly zero local emissions [205]. The conventional aircraft uses no electrical power or electrical energy for propulsion, hence $H_P = 0$, $H_E = 0$.

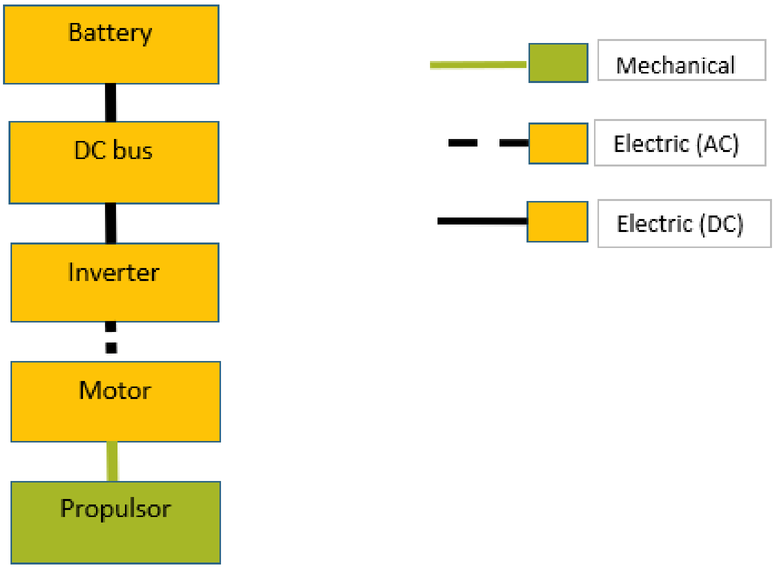


Figure 14 – All-electric system configuration.

A turboelectric system, Figure 15 [204], in an aircraft uses aviation fuel for energy storage, but electrical power transmission instead of mechanical power to drive the propulsors ($H_P > 0$, H_E

= 0). This configuration does not rely on batteries for propulsion energy through any phase of the flight. Instead, the gas turbines are used to drive electrical generators, which will power the inverters and the motors that drive the propulsion.

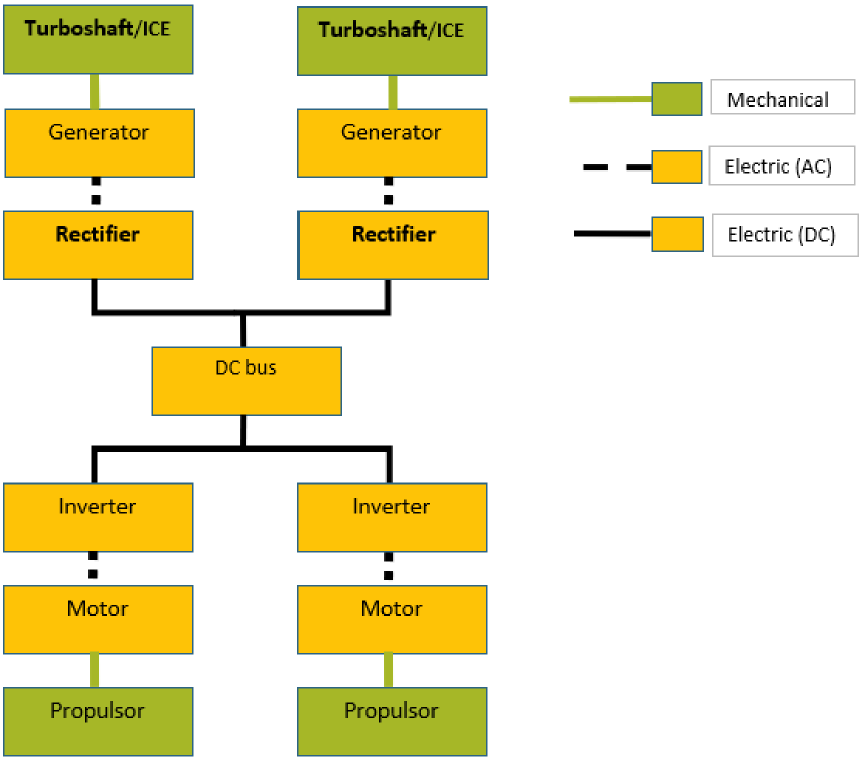


Figure 15 – Twin turboelectric system.

A hybrid electric system uses a combination of aviation fuel and electrical energy storage for thrust, where $H_P > 0, 0 < H_E < 1$. An engine is used for propulsion and for charging the batteries, while the batteries also provide energy for propulsion during the flight [206]. There are two types of hybrid systems, serial and parallel.

A parallel hybrid system delivers the power to the propulsor mechanically ($H_P < 1, 0 < H_E < 1$), Figure 16 [204]. An engine and an electric motor driven by batteries, are attached on the same shaft, and the shaft drives the propulsion. This is done so that either one or both can provide propulsion at any given time [207]. The batteries react to quick changes and high power demands and can therefore be used when there is a need for peak loads during a flight, for example during takeoff. One disadvantage with this system is the risk of a shift of the operating line for the gas turbine, since the gas turbine and the electrical motor run on the same shaft. This can cause part-loading and will, therefore, decrease the efficiency [205].

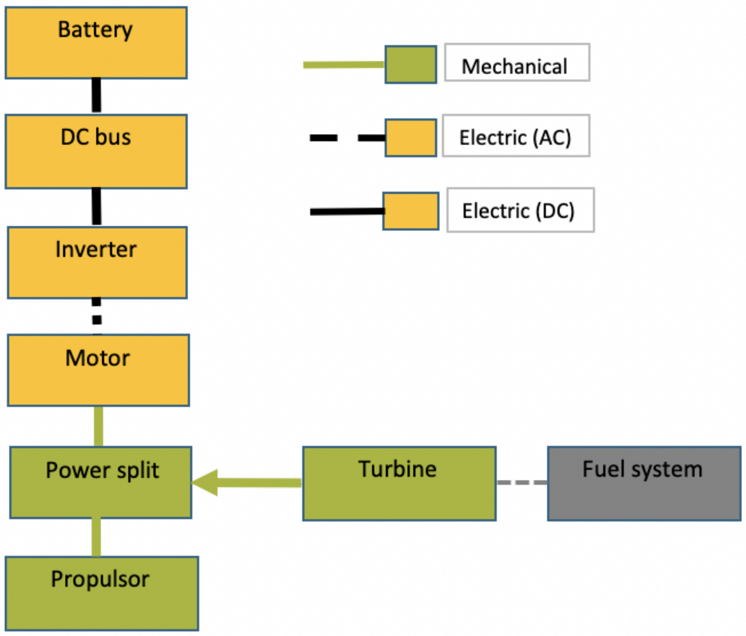


Figure 16 – Parallel hybrid system.

A serial system generates electrical power using a combustion engine and delivers both energy from the battery and aviation fuel to the propulsion via the electrical bus ($H_P = 1$, $0 < H_E < 1$), Figure 17 [204]. Different designs are possible with a serial hybrid system; one of them is that the batteries can recharge during the flight. This is achievable under phases of a flight with lower power demands. The serial system has a separate combustion engine connected to the generator. The combustion engine can be a piston or a turbine, and it generates electricity for the battery pack. The electric motor operates the propulsion. A serial system has the capacity to distribute several electrical fans alongside the wings of the aircraft, which will increase the overall efficiency [205]. To split up the propulsion system can enable each component to be designed and optimised separately [208]. Such a system can be challenging to apply to an existing aircraft since the gas turbine and the electric motor must be designed together in one coherent system.

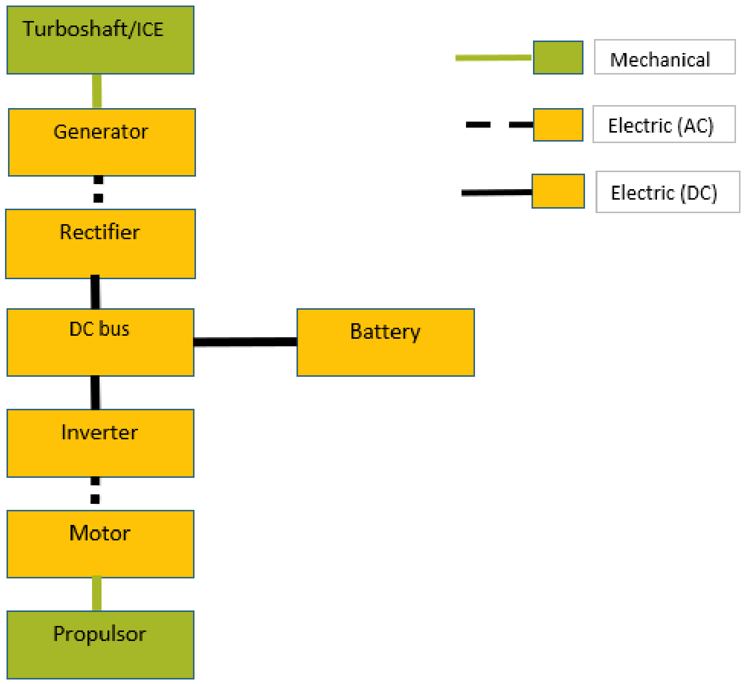


Figure 17 – Serial hybrid system.

It is also possible to combine these two hybrid systems, parallel and serial, into one fused concept. The engine and the electric motor will produce the necessary thrust for the aircraft as in the parallel system concept [205]. However, the two systems are mechanically disconnected from each other. It is possible to connect another generator that can give power directly to the electric motor or charge the batteries. A system like this can be used in modern aircraft design.

Another form of hybridisation can be accomplished by combining a fuel cell and a battery with an electric motor, such as Figure 18 suggests. The fuel used is hydrogen, and the battery will be used to cover the peak power loads during takeoff and climb. The electric motors use the power generated to propel the aircraft. Figure 19 shows the propulsion system with only hydrogen, although this can be viewed as novel in its implementation.

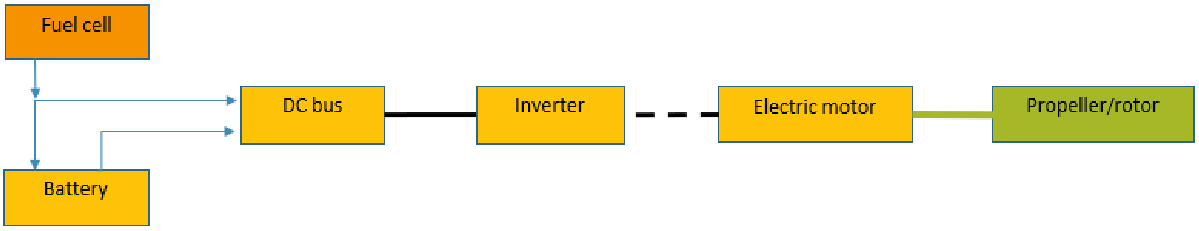


Figure 18 – Hydrogen and battery propulsion system.

Figure 19 – Hydrogen propulsion system.

2.4 Conclusion of literature study

There has been an increase in the development of sustainable propulsion systems in aircraft in recent years. Today, several projects have been identified, some more optimistic than others; however, most of these cases apply for smaller aircraft. The certification process can be long, with weight and range issues common. It is, therefore, easier to modify an existing aircraft design.

Battery technology, hydrogen and biofuels can act as alternative propulsion methods. Considering batteries, there is just a question of time before a leap in technology development can increase the energy density significantly. SSB and Li-S batteries are both considerable battery technologies, along with the more established LIB. Technologies in development such as Li-air and SiO_2 also show promise; however, they are potentially decades away before being commercially available. In the future, the industry might need to look for other key materials in addition to lithium.

Hydrogen is another option, as this propulsion system has no GHG emissions if the production method leads to no further emissions. A storage method such as low pressure CGH_2 in combination with a PEMFC can be suitable here. Biofuels can be a compromise for now, as it can be a carbon neutral alternative fuel, however not a permanent solution. In addition, one needs to ensure that the biofuel production chain is sustainable. For propulsion systems, the overview shows that there are different concepts and that there are numerous opportunities to make an aircraft more sustainable. An electric plane, for example, will have fewer components, while a hybrid-electric configuration will be more complicated. Choosing a fitting concept depends on the design and what the aircraft should be used for. Also, passenger numbers and range play a dominant role in the final propulsion concept.

3. Case study

3.1 The short-haul network

Norway has a unique short-haul network of airports that connect the districts to the central parts of the country. The country's topography is challenging the development of road infrastructure and therefore requires air transportation across longer distances. As a result of political decisions made in the 1960s and early 1970s to meet the demand for better infrastructure, several small airports were built. The runways were constructed with a length of 840 meters and 30 meters wide, and these became a supplement to the existing lager airports [209]. Today, there are 45 airports in Norway; eight of them are defined as large airports. These are Oslo, Bodø, Bergen, Stavanger, Kristiansand, Trondheim, Ålesund and Tromsø. The remaining 37 airports require smaller airplanes due to the short runways. The Norwegian government established Avinor AS to operate most of the country's civil airports as well as all air traffic control services [210].

The airline Widerøe dominates the short-haul network in Norway; as 75 % of their flights cover distances shorter than 300 km, their aircraft are designed to operate on 800 meter long runways. Some of these local routes are simply financially unviable for an airline to operate without subsidy. Therefore the Norwegian government operates a tender system in order to maintain these routes. These are also called PSO (Public Service Obligation) routes [211], and most of them connect Western and Northern parts of Norway to the larger regional airports. In some cases, the government can also offer subsidies to the airline applying for the PSO route over a limited period [212]. Apart from Widerøe dominating the PSO routes [213], the airlines SAS and Norwegian Air Shuttle cover the regional routes between the larger airports.

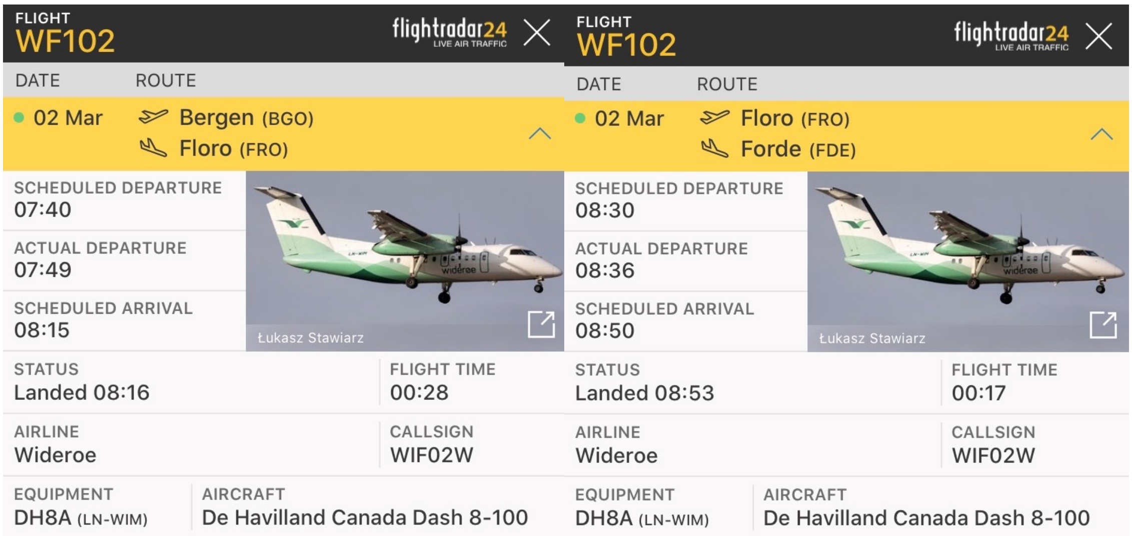
Because of the short-haul network of airports and the market established [214], Norway has a good foundation and potential for implementing sustainable propulsion on several flight routes.

3.2 Potential routes in Norway

This thesis will mainly focus on one route in order to go more in-depth so that the potential route can be more thoroughly evaluated and discussed. However, this can be applied to other routes of a similar distance.

Initially, various routes in the Northern part of Norway are addressed due to the short distance between the airports such as Vadsø, Berlevåg, Mehamn, and Honningsvåg. Factors such as weather conditions, temperature and demand are evaluated. The weather in northern Norway is more extreme than in southern parts of the country. Weather conditions such as headwinds can increase the use of power, since the temperature is, on average, lower. For a battery the temperature in the cells will decrease with the temperature of the surroundings, which will result in a reduced performance [215].

Another flight route that is considered was Bergen - Florø - Førde (Figure 20 [216]), located in Western Norway. The flight time from Bergen to Florø is 35 minutes, and 20 minutes from Florø to Førde, with a current turnaround time in Florø of 15 minutes. If it was judged necessary to charge the aircraft's batteries, the schedule for this route is, consequently, seen as inconvenient and highly limiting with current battery charge times. This also excluded other routes that only have a turnaround time of 15 minutes.



FLIGHT
WF102

DATE	ROUTE
02 Mar	Bergen (BGO) Floro (FRO)

SCHEDULED DEPARTURE
07:40

ACTUAL DEPARTURE
07:49

SCHEDULED ARRIVAL
08:15

STATUS
Landed 08:16

FLIGHT TIME
00:28

AIRLINE
Wideroe

CALLSIGN
WIF02W

EQUIPMENT
DH8A (LN-WIM)

AIRCRAFT
De Havilland Canada Dash 8-100

FLIGHT
WF102

DATE	ROUTE
02 Mar	Floro (FRO) Forde (FDE)

SCHEDULED DEPARTURE
08:30

ACTUAL DEPARTURE
08:36

SCHEDULED ARRIVAL
08:50

STATUS
Landed 08:53

FLIGHT TIME
00:17

AIRLINE
Wideroe

CALLSIGN
WIF02W

EQUIPMENT
DH8A (LN-WIM)

AIRCRAFT
De Havilland Canada Dash 8-100

Figure 20 – Bergen - Florø – Førde.

Other routes in the western region are further investigated, with the criteria that they have to be of short duration and not consist of transit flights. In November 2019, the newspaper Bergens Tidende reported that several businesses in the Stavanger region aimed to electrify the route between Bergen and Stavanger by 2023 and be the world's first commercial route for electric propulsion [217]. The route also seems to qualify for the criteria set for this thesis, since the flight distance and duration is not too long nor too short.

3.2.1 Bergen - Stavanger

The flight route between Bergen airport, Flesland, and Stavanger airport, Sola, has a duration of approximately 35 to 40 minutes, with a distance of 160 km. In 2019 there were over half a million travelers between Bergen and Stavanger as Table 11 shows [218], and it is estimated to be nearly 20 to 25 departures and arrivals every single day [219]. This indicates that the route is quite popular, and one of the reasons is that workers in the offshore industry often commute between the two cities. The airport in Bergen is also Norway's second largest airport and is estimated to handle up to 7.6 million travelers per year [220]. Stavanger Airport is Norway's oldest civilian airport and had a total of 4.3 travelers in 2018 [221].

Table 11 – Annual passenger number between Bergen and Stavanger, see *Attatchement 1*

Year	Passengers
2019	510 508
2018	492 816
2017	486 017

Three airlines operate the route on a daily basis; Norwegian Air Shuttle, Widerøe, and SAS, all with different aircraft types and various passenger numbers, as shown in Table 12.

Table 12 – Airlines and aircraft types.

Airline	Aircraft type	Seating config.	Source
Widerøe	De Havilland Canada DHC-8-400 Dash 8Q (DH4)	78	[222]
	De Havilland Canada DHC-8-300 Dash 8Q (DH3)	50	[222]
Norwegian	Boeing 737-800 (73H)	186/189	[223]
SAS	Boeing 737-700 (73G)	141	[224]
	Bombardier Regional Jet 900 (CR9)	90	[224]

3.2.2 Hypothetical sustainable route between Bergen and Stavanger

This section will look at the possibilities for a more sustainable propulsion system on a potential aircraft between Bergen and Stavanger with the passenger number from 2019. The number of flights with respect to the airlines operating the route and the passenger load factor (PLF) will be assumed on a given day. The PLF is the number of actual passengers on board the plane. This study will focus on a 19 seat aircraft since there is no need for cabin crew and lavatories; this means that the aircraft will be lighter and have lower operational costs [225]. Moreover, to chose a larger aircraft would result in a higher mass, which, according to Section *2.1.3 Challenges*, would lead to an increase in the power requirements. The selected aircraft will be further elaborated on in Section *3.3 Aircraft*.

A spreadsheet has been constructed to show the number of flights per day between the airports, passenger numbers for different airlines and the respective aircraft types. Then, the same numbers are used to calculate the scenario with a 19 seat aircraft, with the possibility to change the PLF. A travel plan for one aircraft will also be presented.

In 2019 there were 510 508 travelers between Bergen and Stavanger. If a 19 seat aircraft is used, 26 869 flights will be required. On a specific day in Bergen, there were 16 departures and 16 arrivals to and from Stavanger; 32 flights in total. SAS has around 62 % of these flights. With 32 flights a day the PLF is assumed to be between 65 and 75 %. SAS, Widerøe and Norwegian is respectively operating a Boeing 737-700 (73G) and Bombardier Regional Jet 900 (CR9), a De Havilland Canada DHC-8-400 Dash 8Q (DH4) and De Havilland Canada DHC-8-300 Dash 8Q (DH3), and a Boeing 737-800 (73H). The resulting number of travelers is 2 922. For this reason, 154 flights per day are required if a 19 seat aircraft is used, assuming that the PLF is 100 %. This is assuming that the demand will be constant at all departure times throughout the day and week.

Table 13 and 14 are just examples of how one aircraft can operate this route. All times are in UTC+01.00 for the purpose of convenience, although UTC is the time standard used in the aviation sector (formally GMT or Greenwich Mean Time). The first flight is set to depart at 07:00 from Flesland, and the last flight has an arrival time at 22:40. For this reason, one aircraft will have ten flights per day; but some assumptions have been made to complete ten flights. The aircraft will have a turnaround time of 60 minutes. This is to provide sufficient time for charging to give the possibility for the scenario where a rechargable aircraft was used. Passengers disembarkation and embarkation along with loading and ground inspections would also take place within this period. This means that the number of required aircraft for one day is 16; 9 with SAS, 4 with Norwegian, and 1 - 2 with Widerøe.

If a battery swap system is implemented, it will be assumed that the turnaround time can be reduced to 30 minutes. One aircraft can, therefore, make 14 flights per day as shown in Table 14. This would imply that 11 aircraft are required to operate the route. The aircraft will in reality not be set to depart and arrive all at the same time, and will be spread out more evenly throughout the day.

Table 13 – Travel plan with charging.

Travel plan with charging			
Bergen		**Stavanger**	
Arrival	**Departure**	**Arrival**	**Departure**
	07:00	07:40	08:40
09:20	10:20	11:00	12:00
12:40	13:40	14:20	15:20
16:00	17:00	17:40	18:40
19:20	20:20	21:00	22:00
22:40			

Table 14 – Travel plan with battery swap.

Travel plan with battery swap			
Bergen		**Stavanger**	
Arrival	**Departure**	**Arrival**	**Departure**
	07.00	07.40	08.10
08.50	09.20	10.00	10.30
11.10	11.40	12.20	12.50
13.30	14.00	14.40	15.10
15.50	16.20	17.00	17.30
18.10	18.40	19.20	19.50
20.30	21.00	21.40	22.10
22.50			

3.3 Aircraft

This section aims to identify the aircraft type that will be modified to a more sustainable propulsion system. The feasibility of 3 different propulsion systems will be investigated: all-electric, hydrogen and hybrid electric. The method used for the necessary calculations are presented in Section *3.3.7* to *3.3.9*. The selected aircraft shall fulfil the criteria for operating the route between Bergen and Stavanger, and the calculations are, therefore, based on that route. The numbers and results are presented in Chapter *4. Results*.

Before all else, an aircraft type had to be chosen. Different 19 seaters were considered, such as the BAe Jetstream 31/32EP [226], Dornier Do228 [227] and de Havilland Canada DHC-6 Twin Otter 400 [228]. The aircraft selected was the Twin Otter 400 series with two turboprop engines. The Twin Otter has a long history, as the first model, the -100 series, had its maiden flight in 1966 [229]. Originally produced by de Havilland Canada, the Twin Otter was built to overcome harsh environments and challenging topographical landscapes with short runways. Today, the production rights are owned by the Canadian based manufacturer Viking Air [228]. Widerøe started utilising the plane on their regional flight network from the late 1960s up to 2000 [230]. Indeed, the Twin Otter is no stranger to the Norwegian short haul network, and it is still flown by several airlines around the world today. Several series have been built to this day, improving the aircraft's overall performance. In Table 15, the key information for the Twin Otter is presented [231], however the data may vary based on what type of configuration the aircraft is using.

Table 15 – Specifications for DHC-6 400 Twin Otter.

Max. cruise speed sea level	(kt)	170	(m/s)	87.5
Max. cruise speed 5000 ft	(kt)	181	(m/s)	93.1
Max. cruise speed 10 000 ft	(kt)	182	(m/s)	93.6
Max. cruise altitude	(ft)	25000	(m)	7620
Fuel Capacity + option	(US gal)	378 + 89	(l)	1 432 + 336
Fuel-burn at cruise (economic 10 000 ft, 146 kt)	(lbs/hour)	468.2	(kg/hour)	220.5
Range + option (zero payload)	(nm)	799 + 190	(km)	1 480 + 352
Maximum endourance + option	-	-	(h)	6.94 + 1.82
Takeoff distance	(ft)	1 200	(m)	366
Landing distance	(ft)	1 050	(m)	320
Rate of climb at sea level	(ft/min)	1 600	(m)	488
Payload weight: 100 nm | 185 km	(lbs)	4 061	(kg)	1 842

Payload weight: 400 nm | 741 km	(lbs)	3 031	(kg)	1 375
Max. takeoff weight	(lbs)	12 500	(kg)	5 670
Max. landing-weight	(lbs)	12 300	(kg)	5 579
Empty weight	(lbs)	7 100	(kg)	3 221
Fuel weight + option	(lbs)	2 576 + 614	(kg)	1 169 + 278
Crew	-	-	(#)	1 - 2
Passenger	-	-	(#)	≤ 19

3.3.1 Fuel numbers

The fuel numbers are used as a basis to calculate the energy need required for the chosen route. This is in order to simplify the calculation prosess, as a greater extent of factors will have to be considered to retrofit an aircraft. In order to carry out such a project in real life, one should be more familiar with the aircraft's technical specifications in order to make more advanced calculations. The fuel numbers have been generated by the flight planning program RocketRoute, and are based on the route between Bergen and Stavanger with a specific amount of passengers and bags, see Section *3.3.2 Load*. Alternate airport is ENHD, Haugesund airport, Karmøy. The four digit airport code is an ICAO standard for designating an aerodrome. The following fuel numbers were generated. An overview of how these numbers are generated can be found in *Attatchment 2*.

Table 16 – Fuel numbers for Bergen - Stavanger.

Fuel	**lbs**	**kg**
Trip	305.00	138.35
+ Dest. Contingency	9.00	4.08
+ Alternate (ENHD)	118.00	53.52
+ Alternate Contingency	4.00	1.81
+ Final Reserve	240.00	108.86
+ Holding fuel	246.00	111.58

+ Additional fuel	0.00	0.00
Minimum takeoff fuel	**922.00**	**418.21**
+ Taxi fuel	100.00	45.36
Off block	**1022.00**	**463.57**
Burn (taxi + destination)	405.00	183.70

The amount of taxi fuel is usually set for an average taxi time. This amount can change because of the local conditions at the departure area and other common ground delays [232]. A full sheet of the fuel numbers generated can be found in *Attatchment 2*.

3.3.2 Load

The number of males, females, children, crew and bags is calculated with RocketRoute, and the weight is standard for the program. There is a requirement of two pilots for every flight [225]. An overview of how these numbers are generated can be found in *Attatchment 2*.

Table 17 – Weight of passenger, bags and crew.

Weight pax	**lbs**	**kg**	**Amount**	**lbs**	**kg**
Male	207	93.89	9	1863	845.04
Female	165	74.84	9	1485	673.58
Child	73	33.11	1	73	33.11
Baggage	37	16.78	10	370	167.83
Crew	170	77.11	2	340	154.22
				Total	**1873.78**

3.3.3 Propulsion system

The Twin Otter has had several propulsion configurations throughout the decades. The aircraft has two turboprop engines produced by Pratt & Withney Canada, the PT6A-series. Table 18 describes the various engine variants and their respective dry weight. This includes basic engine, fuel and ignition systems; however, excludes the ignition power source, propeller governor, plus fuel and oil reserves.

Table 18 – Twin Otter engine specifications.

Series	Engine (Turboprop x 2)	Power	Dry Weight	Source
100	PT6A-20	431 kW / 578 shp	286 lbs / 130 kg	[233] [234]
300	PT6A-27	460 kW / 620 shp	337 lbs / 153 kg	[233] [234]
400	PT6A-34	559 kW / 750 hp	340 lbs / 154 kg	[234] [231]

There are currently only a few electric motors designed for aircraft, and especially with a similar power to the Twin Otter's 559 kW turboprop engine. The industrial manufactor Siemens AG have produced two types of electric motors designed for aircraft and to fit a turpoprop airplane; The *SP260D* and *SP200D*, with a respective 260 and 204 kW power output and a weight of approximately 50 kg. That gives an ideal power-to-weight ratio of 5.2 - 5.9 kW/kg. The improvement of technologies to enhance power density can result in an electric motor weight of 100 kg for a Twin Otter, which is the turboprop motor power of 559 kW divided by the average power-to-weight ratio of 5.5 kW/kg. This leads to a weight saving of around 2 x 54 kg compared with the PT6A-34 engine weight of 154 kg [235]. Therefore, it is assumed a weight saving of 50 kg for each electric motor in this case.

MagniX has designed a suitable electric motor for the purpose of retrofitting excisting aircraft such as models from Cessna and King Air, as well as the Twin Otter. The *magni500* delivers continuous 560 kW power with an efficiency of over 93 %. The motor has a liquid cooling system and a weight of 133 kg. For a Twin Otter, this results in a weight-decrease of about 20 kg for each engine. This motor is already used on Harbour Air's DHC-2 Beaver [236].

For calculation, the study has used the average value for the motor weight based on Siemens' and MagniX's technology, (100 kg + 133 kg) / 2 = 116.5 kg. This results in a final weight saving of 37.5 kg per electric motor.

3.3.4 Weight savings

As mentioned in Section *2.2 Energy storage*, there is a need for weight savings, since an energy source, such as a battery, is 26 times heavier than jetfuel with present day technologies. That said, there will be no need for the components related to the turboprop engine on board. This will result in weight savings from removing the fuel system which consists of tanks, pipe, lines, pumps, filters and valves for the fuel, as well as quantity sensors, wiring and computers. Further, it is possible to save weight by replacing the control cables with a fly-by-wire system, and also the hydraulic system with electric driven actuators and controllers.

With the fly-by-wire system the pilot will not have direct contact with the flight control surfaces. The mechanical connection is replaced with an electric interface. The mechanical flight stick connected to control cables, pulleys, quadrants and push-pull rods, are replaced with electrical wires or fibre cables, and digital computers. Further, the control surfaces that normally are driven by hydraulic actuators can be replaced with an electrical motor-controlled-actuator and feedback sensors. Fly-by-wire was first used in the supersonic passenger airliner BAC Concorde as well as military aircraft. Present day commercial passenger airplanes such as Airbus A380, A320-series and Boeing 777 and 787 Dreamliner now use this system. A digital flight control system will likewise take up less volume than an analoge-hydraulic concept [237].

Components that can be replaced within the hydraulic system are the hydraulic reservoir, hydraulic lines, valves, the hydraulic filter, accumulator system for the system and brakes, pumps and the motors. Other measures that airlines have taken in order to save weight are to install lightweight seats, increase the use of carbon fibre for the airframe, and intergrate and modernise the avionic system. Viking Air has made avionic improvements since the production startup of the -400 series and the study does not have an overview of further improvements from the company [238]. An electric aircraft will need an inverter and a DC bus to transfer the power from energy source to the motor(s) and propulsion system. Cables can lead to a weight increase. Assumptions for these weight savings is taken from the discussion above and a presentation given by Bombardier at the *Aviation Operational Measures for fuel and Emission Reduction* conference [239]. An overview over system replacements can be found in Table 19.

Table 19 – System replacements

System / Component	Replaced by
2 x PT6A-34 Turboprop egine	2 x Electric motor
Fuel System	Battery / Hydrogen
Hydraulic system	Electric system
Flight Control System	Fly-by-wire system
Modenise and intergrate the avionic system	-
Material- and structure improvements	-

As mentioned, one can use new technology materials that can replace most of the aluminium structure, such as composite or plastic materials. Today the only materials that use carbon fibre is the radome [231]. The primary structure of the aircraft wings and fuselage are all made of aluminium alloy, and could be a potential for significant weight savings. For Boeing's Dreamliner project this resuled in a weight saving of 20 % compared to a similar aircraft using a completely aluminium alloy structure [240]. That gives a potential for a weight saving of 644 kg, based on the aircraft's empty weight. This could lead to a huge change in the structural design, and might need recertifications. For Twin Otter an easy way to save weight is to use composite materials on non-primary structure parts such as fairings and access panels.

For this study, the required calculations in Chapter *4 Results* is based on the weight assumptions which will not result in a complicated re-design. Table 20 shows the weight savings assumed for the all electric and hydrogen propulsion system in Section *4.1* and *4.2*.

Table 20 – Assumed weight savings for all electric- and hydrogen propulsion.

Weight savings	lbs	kg
Fuel system	110.	50
Hydraulic system	44	20
Flight controls system	110	50
Material improvements	110	50
Propultion systems	165	75
Modernise avionic	22	10
Total	**562**	**255**

Table 21 shows the weight savings assumed for a hybrid electric propulsion system in Section *4.3*.

Table 21 – Assumed weight savings for hybrid electric propulsion.

Weight savings	**lbs**	**kg**
Fuel system	55	25
Hydraulic system	44	20
Material improvements	110	50
Modernise avionic system	11	5
Flight controls system	110	50
Total	**331**	**150**

3.3.5 Efficiencies

Several steps must be taken into account in order to determine the overall efficiency. For an all-electric propulsion system the energy from the battery output is lead to the inverter through the wiring system (DC bus lines), and then to the electric motor. From the motors, the power is transferred to a shaft that is rotating the propeller, which is the essential device that makes the aircraft accelerate. The energy source will not only feed the electric motor, but also the avionic system on the aircraft. This includes lights, navigation and radio system, fans and cooling system, de-ice system, cockpit voice recorder, flight data recorder, and flight control system. As already done in aircraft today, it is assumed that an external battery will feed the backup systems in case of an emergency. This backup battery will handle the most essential instruments and the flight control system, and allow power cross flow between the main power battery. For the calculation of the battery efficiency, it is assumed that about 1 % of the battery power goes to heat loss, and 4 % to operate the avionic system. For the transfer lines (DC bus) and the inverter, it is assumed a heat loss of 1 % for each system, and therefore an efficiency of 99 %. Multiplying all the efficiencies leads to an overall efficiency of 87 % for all-electric propulsion.

The main battery should be compromised of two independent units, each ordinarily connected to a respective propulsion motor. There should be the possibility of redirecting power from either of the two battery units to either of the propulsion motors in case of an emergency. That way, if either battery unit or propulsion motor failed the aircraft could provide the regulatory airfield and in-flight performance. The electric propulsion motor that will replace the turboprop PT6A engine must represent the same output shaft power to the propeller.

For hybrid electric propulsion, the efficiency depends on the ratio between the battery and jetfuel and the type of propulsion system. The mentioned efficiencies can therefore also be applied to the electric parts of the system. No specific propulsion system will be chosen in this thesis, however the fraction of energy jetfuel and electricity will later be determined in Section *3.3.9. Hybrid electric propulsion calculation*.

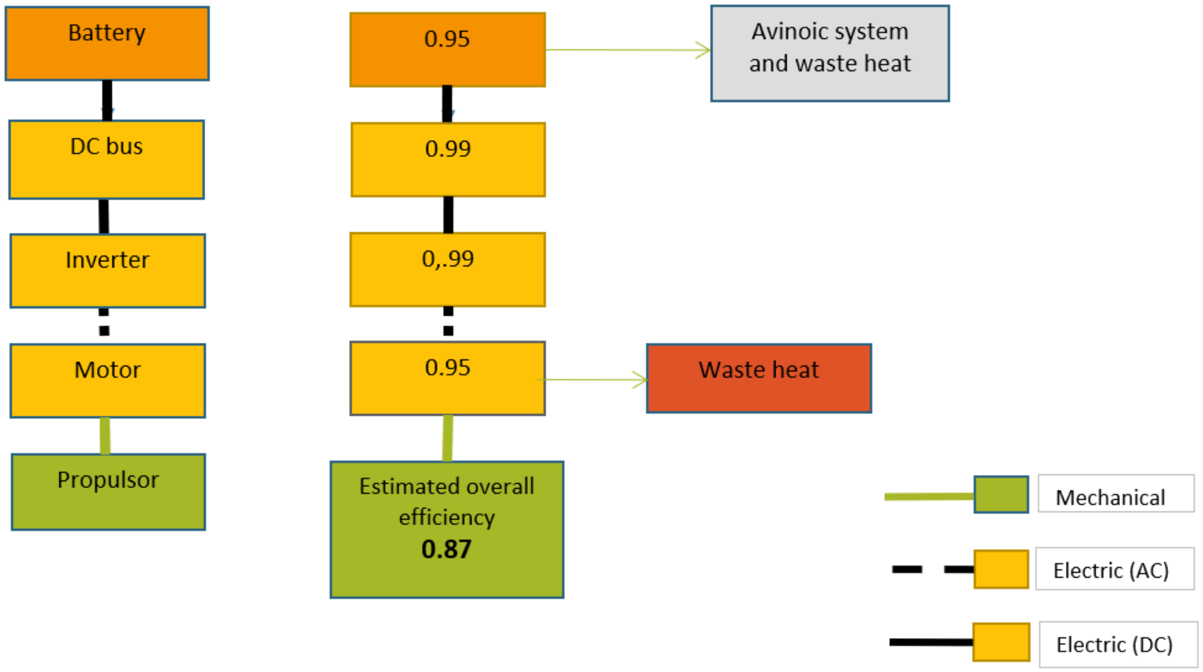


Figure 21 – Efficiencies for the all-electric system.

It is complicated to calculate the specific efficiency of a Twin Otter engine, so a series of assumptions will be made. The total efficiency for the PT6A engine depends on the combustor, compressor turbine, power turbine, and the mechanical transfer to the rotor and propeller shaft. From Figure 22 [206] (p. 40), the chart from National Academic Press describes an overview of the thermodynamic efficiencies for several aircraft engines. Based on the graph an efficiency of 25 % is assumed for the PT6-A34 engine.

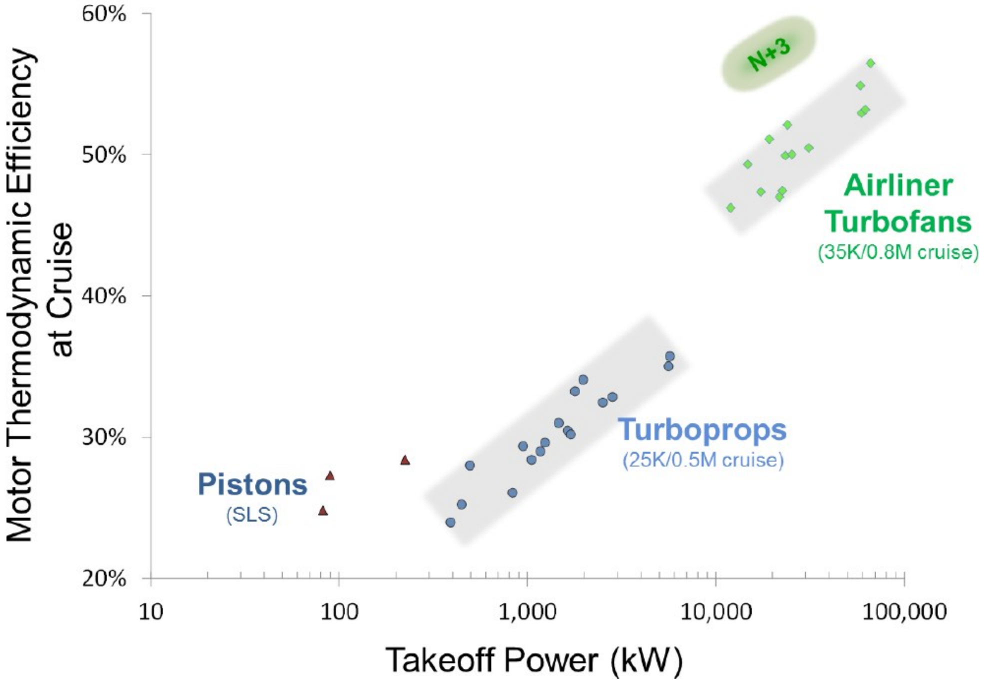


Figure 22 – Overview of motor efficiencies compared with engine type and takeoff power.

For the hydrogen system, it is assumed that the fuel cell is a PEMFC as this type is fitting for mobile applications. All efficiency losses connected to the fuel cell has an estimated efficiency of 50 %. Energy losses connected to the BoP of the fuel cell is neglected. The hydrogen is converted to electric energy in a fuel cell before it passes to the electric motor through the inverter and the wiring system. The overall efficiency of the system would result to 47 % as seen in Figure 23. A hydrogen system would need two sections of fuel cells and storage tanks for each electric motor, so that if either fuel cell unit or propulsion motor failed, the aircraft could still provide the same performance.

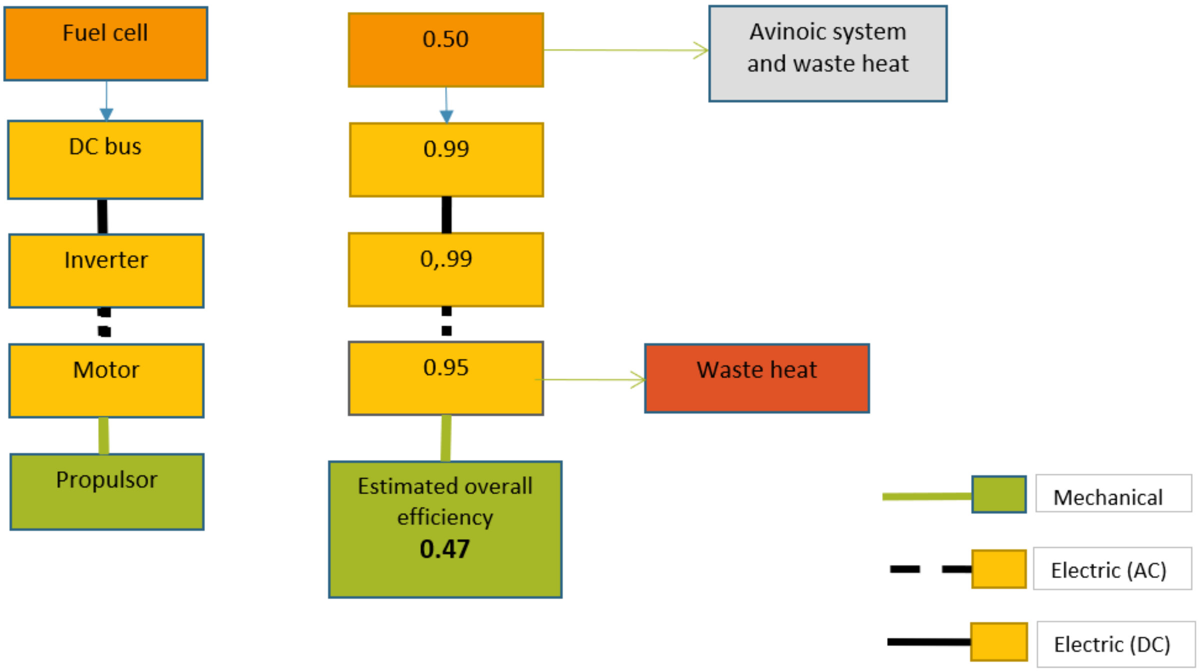


Figure 23 – Efficiencies for hydrogen propulsion.

3.3.6 Heating

There is no hot bleed air in an electric aircraft due to the high efficiency og electric motors compared to engines as seen in Section *3.3.5. Efficiencies*. When at high altitudes with cold temperatures, it is necessary to heat the airplane in some way. This is essential to consider, especially for the cold climates in Norway, and for aircraft that have a high service ceiling. In a turboprop based hybrid aircraft, the waste heat from the engines can be used to heat the cockpit and cabin.

An electric motor is still in need of a cooling system. The MagniX project has faced problems to get sufficient cooling air to reduce the electric motor temperature due to the aircraft's low speed. This was solved by using a liquid cooling system, but this defeated the purpose of having a light and powerful motor [241]. By way of comparison, in EVs the loss of a heat source from an internal combustion engine has been solved by using heater elements and/or heat pumps; where the latter reduces the power requirement, but will add weight. This requirement for heat will result in a shorter range for an aircraft at lower temperatures.

Another common problem is that the lowering the temperature increases the internal resistance in batteries and leads to a further decrease in power [242]. However, large battery packs with the current commercial technologies, such as LIB, have the issue of producing heat during charge and discharge due to enthalpy change, which may increase the risk of thermal runaway for the same reason. In a cold surrounding atmosphere, the battery might need to utilise its own heat energy loss to maintain a warmer local environment, in order to remain at an adequate and stable performance/efficiency. Additional waste heat could be used for de-icing, or to heat up the cockpit and cabin in case the heat energy loss causes the surroundings of the battery to become too warm.

Similarly for a hydrogen propulsion aircraft, the waste heat from the operating temperature of the fuel cell can be used for heating. A PEMFC operates at a temperature between 50 - 90 °C, where the hot air can be mixed with re-circulated air from the cabin to maintain a comfortable temperature.

3.3.7 All-electric propulsion calculation

The electrification project with Harbour Air Seaplanes currently use batteries with a specific energy density of 135 Wh/kg, but expects 400 Wh/kg units to be available when the certified aircraft are ready for commercial passenger flight. Its design for 6 passengers has an expected flight time of 30 minutes and a 30 minutes power reserve, which challenges this study with a 19 passengers aircraft and flight duration of 40 minutes [243].

Based on future battery technologies, the study will use an optimistic energy density of 500 Wh/kg for calculations for the DHC-6 Twin Otter. As mentioned in Section *2.2.1 Battery*, there is only a matter of time before LiS and SSBs can revolutionise the battery industry. This study has not taken the C-rate of batteries into account. An aircraft would in theory need batteries with a high C-rate that can provide high power in a short period of time for the takeoff phase.

By using the fuel numbers from Section *3.3.1 Fuel numbers*, the amount of net energy content (J) is calculated. This is done by dividing the calculated amount of required fuel (kg) by the specific energy for Jet A-1 fuel (J/kg). Further, the net energy content (J) is multiplied with the efficiency of the PT6A-34 engine (%), resulting in the actual energy used for the flight (J). The energy that is required for the electric motor is the actual energy used for flight (J), divided by the total efficiency for the electric plane (%). These results are used in further calculations. Conversions between J and Wh and between lbs and kg have been made wherever needed.

The battery weight (lbs) is calculated by using the required energy for an electric aircraft and dividing this by the energy density of the battery (Wh/kg). Total load and total weight savings are then subtracted from the battery weight. The result shows the overweight with and without passengers and bags. Results and numbers are shown in Section *4.1 All-electric propulsion system.*

3.3.8 Hydrogen propulsion calculation

It is necessary to calculate the amount of required hydrogen to power the aircraft and the weight and volume for the hydrogen tanks. Respective calculations will be made for LH_2 and CGH_2 with 300 bar and 700 bar pressure.

The weight of the fuel cells is unknown. A battery is likely to be included in the powertrain in reality, but was not taken into account in order to simplify the calculation. This will also increase the weight of the aircraft.

The amount of hydrogen (kg) is calculated by dividing the energy required (Wh) on the specific energy (Wh/kg) multiplied with the efficiency (%). The amount of LH_2 (l) is then calculated by dividing the amount of hydrogen needed by the density of LH_2 (kg/l). This will show the volume and should not exceed the fuel capacity (l) for the DHC-6 400, in order to have enough room to store the fuel. The same is done for CGH_2 at 300 bar and 700 bar. The weight of the tanks (kg) is then calculated by dividing the hydrogen volume (l) by the hydrogen to tank weight ratio (%) and multiplied with the density (kg/l). The result should not exceed the available weight minus the weight of the amount of hydrogen needed. Results are shown in Section *4.2 Hydrogen propulsion system.*

3.3.9 Hybrid electric propulsion calculation

The calculations made in this section is a theoretical method in order to find the correct fraction between the energy from battery and aviation fuel. Two calculations are done. The first has a 50 / 50 % relation between jetfuel and batteries. Another calculation is made with 81.6 % fuel and 18.4 % batteries. In order for the aircraft to be in accordance to the maximum weight criteria, only the ratio between battery and fuel will be mentioned. However, concepts for hybrid electric propulsion systems mentioned in Section *2.3.* can be possible for future hybrid electric aircraft. To identify if the relation between fuel and battery is achievable, the weight of fuel and battery must be calculated and compared to the maximum takeoff and landing weight of the aircraft.

First, the energy available from the battery (J) needs to be calculated. This is done by multiplying the actual energy used for the flight (J) with the percentage of the propulsion that the battery should provide (%). Then the result is divided by the total efficiency of an electric aircraft (%). The same calculation is made for the aviation fuel; the actual energy used for flight (J) is multiplied with the percentage of the propulsion that the fuel should provide. Then the result is divided by the efficiency of the PT6A-34 (%).

The weight (kg) of the battery is then calculated by dividing the actual energy from the batteries (Wh) by the energy density of the battery (Wh/kg). The same is done for the fuel, where one divides the actual energy from fuel (J) by the specific energy density of Jet A-1 fuel (J/kg). Conversions have been made between J and Wh when needed. Results and numbers are shown in Section *4.3 Hybrid electric propulsion system.*

A table has then been created with different weight factors for the aircraft. Where the load weight (passengers and bags), empty weight, fuel, and battery weight are subtracted from the maximum landing weight (MLW) and the weight savings are added. The result will show the weight available to transport passengers and luggage (kg). A negative result means that the aircraft is too heavy, while a positive result means that the aircraft has available weight.

An additional table has been made for the aircraft that is operating with 81.6 % fuel and 18.4 % battery.

3.3.10 Aviation certification and regulations

The aviation industry has spent decades making flying affordable and safe. However, the policy and regulations created have made the certification process a complicated bureaucratical system.

Certifications for new aircraft designs can take several years, which makes it advantageous to modify an existing airplane, such as the one this study is focusing on. One can replace the gasoline propulsion and fuel system on an already certified aircraft with, for example, an electrical propulsion system, batteries or hydrogen. This could save the manufacturer several years of certification, as an alternative to designing and manufacturing a brand new sustainable aircraft.

Another problem is the present handling restrictions for LIB. There are aleready strict regulations for passengers to carry lithium batteries for certain laptops and mobile devices onboard [244]. The FAA have regulations for how batteries have to be stored in a suitable container that is safe in the case of a leak or fire. In other words; they are treated as hazardous materials. Some LIBs are banned from passenger transport, and there are additional rules for how much the maximum state of charge should be [245]. Rules like this, if applied, would prescribe having a battery component in an aircraft, which may not be viable. The batteries used in Boeing's 787 Dreamliner in 2013 that had issues with thermal runaway is not conductive to making the certification process for electric aircraft manufacturers any easier. By looking at aircraft projects like Harbour Air Seaplanes could give an indication that a manufacturer would need about 2 years of testing to get an electric aircraft certified by the authorities [243].

As mentioned in Section *2.2.2 Hydrogen*, the fuel is flammable by concentrations of 4 - 75 % in air [181] (p. 34) and can be a potential safety hazard, as higher concentrations can be explosive. A hydrogen leak onboard an aircraft or inside any closed space without an adequate ventilation system can cause serious damage. There are currently restrictions for passengers to bring compressed gas onboard an aircraft [246], and applying such regulations to the CGH_2 as the fuel used to power the plane would not be reasonable.

3.4 Infrastructure

In order for sustainable aircraft propulsion to become realised in Norway, an existing infrastructure needs to be in place. Infrastructure is the network of fixed facilities that form the basis of a business or a system of, for example, roads, ports, airports and wiring networks. The term can also be used in a broader sense to describe the structural assumptions of the content of an activity or product [247]. Present day airports already have much of the required infrastructure available; however, solutions for charging and refueling is needed depending on the sustainable propulsion type.

In the case of numerous electric aircraft arriving at the same time at a given airport, charging could result in so-called power peaks which the airports should be able to cater for [248]. Aditionally, there would be a need for an energy storage solution. There are three scenarios for charging an aircraft: charging directly from the grid, charging from stationary batteries at the airport while the stationary batteries are charged from the grid, or charging from a local grid. A battery swapping system can be implemented, which means that the aircraft switch to a new fully charged battery inbetween takeoff and landing. It could also be necessary to invest in local grids to ensure enough power. A battery swap system would reduce the required level of instant grid power since the charging can be done over a longer time interval [249]. The charging can also be made when power demand is low. With a battery swapping solution, there would be a need for a charging facility, and transport and lifting equipment to swap the aircraft battery with a fully charged unit. Charging the aircraft at the airport would further ensure a safe connection between the aircraft and the charging and supplying infrastructure [249]. These solutions would be up for each airport to decide whether one could utilise the required amount of power directly from the grid or if a battery bank should be installed. Electric car ferries in commercial service in Norway experienced a similar challenge. Some of the ferries are drawing power directly from the grid while charging, and others are using battery banks where sufficient power is not readily available [249]. Regardless of the charging method, one should be aware of the time it would take for the battery to recharge. This could increase the turnaround time which again would affect the flight pattern of an aircraft.

Several factors will play a role if hydrogen were to be used as fuel for aviation. First and foremost, regulations for storage and refueling of hydrogen in all industries in general need to be established. Competence in hydrogen safety and equipment at the airport would also be a requirement. The hydrogen production can take place both nearby the airport or be at an area farther away. If the airport or its close surroundings is home to local production, one can produce hydrogen from electrolysis. Wind turbines or solar panels can generate electricity to the production process. By doing so, the hydrogen is renewable. If the hydrogen comes from external production facilities, one should ensure that the production method is performed through either electrolysis or reforming of hydrocarbons with CO_2 capture and storage. There would also be a need for a secure transportation method, such as by pipelines and road fuel tankers, with fueling stations and mobile storage tanks are needed at the airport. When refueling an aircraft with CGH_2 the transmission pipes should be completely airtight and able to withstand the pressure of the gas. For LH_2, the transmission pipes should have the sufficient insulation and isolation for the liquid to maintain its low temperature. Emergency procedures need to be developed in case of a potential leak, which can be hazardous to the surroundings. In a situation like this, CGH_2 would rise rapidly upwards in the atmosphere and mix with the surrounding air [181] (p. 34), while LH_2 will behave as a dense gas [250].

By using jet biofuel there are no additional requirements for the transportation and storage tanks, as one can use the existing infrastructure for jetfuel. The biofuel can be refueled directly to the aircraft without the need for any added equipment.

As for the situation in Norway, Avinor has declared that smaller private electric aircraft should be exempted from fees and receive free electricity at their airports until the year of 2025. Furthermore, Avinor has taken responsibility to implement an adequate charging infrastructure for electrified aircraft [103].

A project that works with sustainable airport infrastructure is Elnett21; a project that will demonstrate the possibilities to electrify aviation, among other sectors, through various solutions. Based in Stavanger, the aim is also to ensure enough energy to meet future needs [252]. Several major actors in the South Rogaland region cooperate with the project, such as Avinor and Lyse Elnett. The project will showcase how the demand for electricity for aviation, ships and buses can be distributed and managed in order to avoid significant investments in the electricity grid, and will take place during the period of 2019 - 2024 [253]. The power delivery will evolve from today's one-way delivery from grid companies, to create opportunities for electricity sale when needed between the companies involved. Areas surrounding Stavanger Airport can potentially be used for energy production to create a local power supply. Wind and solar energy are relevant renewable energy sources; but various challenges may arise, such as reflection from the solar panels which can be a problem for arriving and departing aircraft. Wind power can contribute to increased wind currents, and can result in more turbulence for the aircraft and may conflict with height restrictions [254]. The power generated from the different energy sources can be stored in batteries at the airport, and by doing so, it is possible to charge the aircraft without the need for electricity from the grid. This solution could potentially be applied to Bergen airport as well as other airports in Norway. The vision of Elnett21 can be seen in Figure 24 [255].

Figure 24 – A possible solution for sale and notification when needed between different businesses.

Another example of sustainable infrastructure is the University of Tromsø School of Aviation (UTSA), Norway's only public aviation school. The school owns two Pipistrel Alpha Electro electric aircraft. They are aiming to charge the two aircraft through power generated from solar cells mounted on the walls of the hangars. The solar cells will produce enough energy for the two planes to be fully self-powered without extracting power from the grid [256].

Another topic related to infrastructure is the human resources. As already mentioned in this section, personnel with competence within the required field will be in high demand. Likewise, there will be a higher demand for pilots in this case study, since the number of aircraft in operation will increase due to the lower seating capacities. Additionally, there will be a lower demand of flight attendants, as this is not required for a plane with 19 seats.

3.5 Conclusion of case study

An overview over the short haul network in Norway identified potential routes to replace with sustainable propulsion. Subsequently, the route between Bergen and Stavanger is chosen due to the passenger demand, and logistical factors for operating the route have been determined.

An aircraft of the type DHC-6 400 Twin Otter was chosen to retrofit for this specific route due to its 19 seat configuration resulting in lower operating costs and weight savings. Further, three relevant propulsion systems from the literature study were approached in order to explore the feasibility for implementing such a propulsion system onboard the aircraft. The fuel numbers and weight assumptions were used to calculate the required energy need for the flight, and used as a basis for what the alternative propulsion systems should be able to sustain. Since batteries and hydrogen both have a higher weight contribution to the aircraft, there are many measures to be taken to decrease the weight and increase the overall efficiency. It would be necessary to find solutions to reuse the heat loss from components to heat the cabin, in order to reduce the need for additional electric heating. Further, the approach for calculating the energy need for the three different propulsion methods are explained thoroughly. Lastly, it is essential to consider the certification process of the aircraft, since a new sustainable design that deviates from a conventional propulsion system can take many years to certify. The authorities needs to ensure that aviation remains safe whithout the regulations discouraging the developement of new propulsion technologies. The infrastructure around sustainable aviation is also discussed, and different propulsion systems will require a different type of infrastructure.

4. Results

The following chapter present the results from the case study. The energy contents of the required fuel amount, energy used for flight, and the necessary energy to the electric motors are first presented in Table 22. The results of the calculations are shown in the following sections.

The amount of energy that is required to power the electric motors are 1.56 MWh.

Table 22 – Calculated energy consumption.

	lbs	**kg**
Fuel uplifted	1 022	464
	J	**Wh**
Net energy content	19 469 998 890	5 412 660
Energy used for flight	4 867 499 722	1 353 165
Energy to electric motors	5 594 827 267	1 555 362

4.1 All-electric propulsion system

Table 23 shows the overweight the aircraft will have with and without passengers and bags when the aircraft is powered by 500 Wh/kg batteries. The aircraft will have an overweight in both circumstances and the same weight during takeoff and landing.

Section *3.3.7 All-electric propulsion calculation* shows what factors the total load and total weight savings contain.

Table 23 – Weight calculation.

	lbs	**kg**
+ Battery weight	7 025	3 186
- Pax and bags	4 131	1 720
- Total weight savings	562	255
Overweight takeoff	**1 649**	**748**
Overweight landing	**1 849**	**839**
Overweight takeoff (with pax + bags)	**5 440**	**2 468**
Overweight landing (with pax + bags)	**5 641**	**2 559**

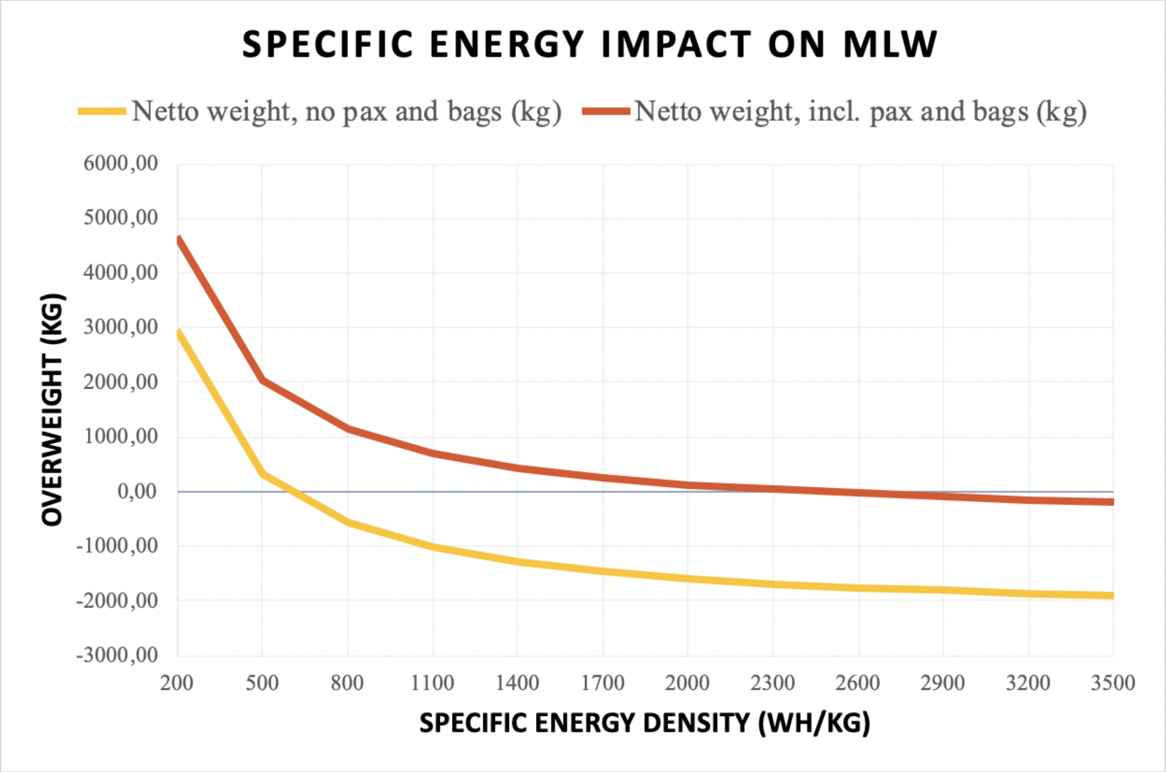


Figure 25 – A battery specific energy impact on maximum landing weight (MLW).

The graph in Figure 25 indicates how much overweight the aircraft will have during landing with the specific energy density for a battery shown in the horizontal axis. When the yellow and red graph reaches the zero-line, the aircraft are within the landing weight limits of 5 669 kg.

The yellow and red graph passes the zero line with a energy density of 679 Wh/kg and 2 539 Wh/kg respectively.

4.2 Hydrogen propulsion system

The amount of hydrogen that is required to power the aircraft is 89 kg.

Table 24 – Calculated amount of hydrogen.

Energy to electric motors	1 488 599	Wh
Efficiency	47 %	η
Specific energy H_2	33 330	Wh/kg
Amount of H_2 needed	**196 | 89**	**lbs | kg**

By using CGH_2 at 300 bar, the aircraft requires 4 466 liters of hydrogen with a weight of 1 076 kg. CGH_2 at 700 bar requires 2 233 liters and 1 489 kg. Both cases exceed the available fuel weight of 704 kg and the available volume of 1 466 liters.

Table 25 – Weight and volume calculation for hydrogen.

	Weight (lbs)	**Weight (kg)**	**Volume (l)**
LH_2	-	-	1 258
CGH_2 (300 bar)	2 372	1 076	4 466
CGH_2 (700 bar)	3 283	1 489	2 233
Fuel cells	-	-	-
Should not exceed	**1 552**	**704**	**1 466**

The weight of the tank required to contain 1 258 liters of LH_2 is unknown. The cryogenic tanks are isolated with a vacuum between an inner and outer layer, and built to withstand both gas diffusion and temperature drops. This leads to more advanced components, and therefore one can only assume that there will be a significant weight penalty when using this storage method. The volume is not exceeding the available volume of 1 466 liters, and therefore there is sufficient space to accommodate the cryogenic tanks.

4.3 Hybrid electric propulsion system

Initial calculations were made with a hybrid electric system that operated on 50 % fuel and 50 % battery. The battery for calculation has a specific energy density of 500 Wh/kg. Table 26 shows the necessary energy for the fuel and battery and the weight of both. The battery will weigh 1 593 kg and the fuel 232 kg.

Table 26 – Calculated energy consumption for 50 / 50 % alternative.

	J	Wh
Net energy content	19 942 841 720	5 544 110
Energy used for flight	4 985 710 430	1 386 028
	J	**Wh**
Useful energy from fuel	2 492 855 215	693 014
Useful energy from batteries	2 492 855 215	693 014
Actual energy from fuel	9 971 420 860	2 772 055
Actual energy from batteries	2 865 350 822	796 568
	lbs	**kg**
Weight of batteries	3 512	1 593
Weight of fuel	511	232
Total	**4 023**	**1 825**

The total weight of the battery and fuel will be 1 825 kg, resulting an overweight of 1 077 kg, as seen in Table 27.

Table 27 – Weight calculation for 50 / 50 % alternative.

	lbs	kg
MLW	12 300	5 579
- Load (pax and bags)	4 131	1 874
- Empty weight	6 850	3 107
+ Weigth savings	331	150
- Fuel	511	232
- Battery	3 512	1 593
Available	**-2 374**	**-1 077**

The second calculation is made with a system that operates on 81.6 % fuel and 18.4 % battery. Table 28 shows the necessary energy for the fuel and battery and the weight of both. The batteries will weigh 586 kg and the fuel 378 kg.

Table 28 – Calculated energy consumption for 81.6 / 18.4 % alternative.

	J	Wh
Net energy content	19 942 841 720	5 544 110
Energy used for flight	4 985 710 430	1 386 028
	J	**Wh**
Useful energy from fuel	4 068 339 711	1 130 998
Useful energy from batteries	917 370 719	255 029
Actual energy from fuel	16 273 358 844	4 523 994
Actual energy from batteries	1 054 449 102	293 137
	lbs	**kg**
Weight of batteries	1 293	586
Weight of fuel	834	378
Total	**2 127**	**965**

The total weight of the battery and fuel will be 965 kg, resulting in an overweight of 217 kg, Table 29.

Table 29 – Weight calculation for 81.6 / 18.4 % alternative.

	lbs	kg
MLW	12 300	5 579
- Load (pax and bags)	4 131	1 874
- Empty weight	6 850	3 107
+ Weight savings	331	150
- Fuel	834	378
- Battery	1 295	586
Available	**-477**	**-217**

Given the overweight, the seat configuration needs to be decreased by three passengers (ie 16 passengers). The amount of required fuel remains the same as for a 19 seater. The aircraft will then have an available weight of 27 kg and meets the requirements for maximum takeoff and landing weight, Table 30.

Table 30 – Weight calculation with 16 passengers for 81.6 / 18.4 % alternative.

	lbs	**kg**
MLW	12 300	5 579
- Load (pax and bags)	3 594	1 630
- Empty weight	6 850	3 107
+ Weight savings	331	150
- Fuel	834	378
- Battery	1 293	586
Available	**60**	**27**

5. Discussion

Some of the results are not feasible as they are. Therefore, one would have to identify where the problem could lie, both within the calculation and the technology. The calculations are highly reliant on weight reducing measures, which again can challenge the certification process. Weight reduction also results in a lower energy need. The calculation method takes, as previously seen, fuel numbers from a specific flight to identify the energy need to further replacing this with an alternative sustainable propulsion method. It is important to mention that the energy consumption calculated is not based on the weight reductions, as these factors depend on eachother. Changing the passenger numbers also change the energy needed. The approach is highly simplified, since one would have to know several more factors and perform more advanced calculations in order to retrofit an aircraft. Factors in the calculations such as efficiencies for the transmission line (DC bus) and inverter might be optimistic.

The program RocketRoute might have estimated numbers that deviate from reality. An example is the empty weight of the Twin Otter, given as 3 107 kg, while the equipped empty weight given from Viking Air is 3 377 kg and with no equipment; 3 221 kg. This will have an impact on the results. Some of the sections within the total fuel uplifted might also deviate from reality, however, the final off block fuel number is believed to be realistic. Upon landing at the destination, there is still fuel left due to operational requirements. This results in additional weight, which, when translating this energy need to an alternative power source with a lower energy to weight ratio, leads to a generally higher mass.

Measures to change the components of the aircraft can also be taken. One can redesign parts of the aircraft by using new technology material, such as cabon fibre, in order to make it lighter. On the other hand, it could be more optimal with a completely new aircraft design that allows the benefits of carbon fibre to be utilised. A new aircraft would also give the manufacturer more control over the overall development and dimensioning of the different components and parts in relation to the weight. However, this would impose an even longer certification process. Changes in structural design can therefore solve a large share of the weight problem.

When considering the three different propulsion methods, one also needs to think about their respective sustainability. Hybrid electric propulsion still leads to GHG emissions, and although these are lower than conventional aircraft's emissions, it should not be a permanent solution. Electric and hydrogen power configurations can, with the right value chain, be completely sustainable, and therefore a better solution in the long run. Hydrogen is a less widespread technology than batteries and requires infrastructural improvement. While battery technology is clearly more developed than hydrogen, insufficient lithium and cobalt resources are a problem in comparison. This is preventing battery technology from meeting the requirements of sustainable propulsion. On the other hand, a hydrogen PEMFC also uses the rare metal platinum [257] as a catalyst [181] (p. 27). Additionally, biofuels can be a temporary solution for fossil and hybrid electric aircraft, both for today and for transitioning to electric and hydrogen propulsion in the future. The use of palm oil as raw material remains an issue with the employment of biofuels. Palm oil production is often connected to the deforestation of rainforest, which are areas with high carbon content and rich biodiversity. Biofuels from palm oil should therefore be avoided.

There are certainly other perspectives that may be added to this thesis. There are other potential solutions for more sustainable propulsion systems. More efficient gas turbines have lead today's aircraft to better utilise the energy in jetfuel. One can also optimise the design of the fuselage and use winglets to decrease the drag. The APU is a small gas turbine that provides heat and electricity to the hotel load of the aircraft, and could potentially be replaced with an electric motor or a fuel cell [258]. Another solution can be to use LNG instead of jetfuel, which has been trialled by the Tu-155 project in the 1980s, and can somewhat reduce the emissions [259].

6. Conclusion and further work

6.1 Conclusion

Three methods of propulsion were investigated by looking at the route between Bergen and Stavanger, in order to assess how the aviation sector in Norway can become more sustainable. The outcomes from the calculations are all highly reliant on weight reducing measures in order to be feasible.

- For an all-electric powertrain, the weight of the battery is too high both for takeoff and landing, and therefore not possible to fly with the required load of passengers. This could be feasible with a future battery technology with a higher energy density. A minimum specific energy density of 679 Wh/kg is needed in order to begin to add passenger and luggage, and one will not be able to carry the full load until the battery reaches 2 539 Wh/kg.
- For a hydrogen propulsion system, LH_2 is more ideal considering volume, however, 300 bar CGH_2 is more ideal considering the weight. In spite of this, the aircraft is still too heavy for takeoff and landing, although more feasible than all-electric propulsion. Additional weight for a fuel cell and battery also needs to be considered when available on the market.
- For a hybrid electric propulsion, a 81.6 % fuel and 18.4 % battery configuration might be possible considering the weight of the battery. This results in an overweight of 217 kg including passengers and bags, thus this configuration can be made feasible by removing three passengers. Therefore, hybrid electric propulsion can be a temporary solution until hydrogen and electric propulsion technologies are at a more mature state. Meanwhile, utilising biofuel mixes in jet fuel may compensate for GHG emissions somewhat. Perhaps future technologies with a higher energy density can allow for larger aircraft with sustainable propulsion.

6.2 Further work

For further work, one should consider to make further weight reductions for the retrofitted aircraft and make more thorough calculations for the hybrid electric propulsion system, or develop a new sustainable plane. The outcome will be affected by existing regulations, and will require an overall change in airport infrastructure.

7. Glossary of terms

Alkali metal. Represents the elements in group 1 in the periodic table; lithium (Li), sodium (Na), potassium (K), rubidium (Rb), caesium (Cs) and francium (Fr).

Alternate fuel. Amount of fuel required to reach an alternate aerodrome.

Avionic. The electronic system on aircraft. Includes navigation-, power- and communication system.

Burn fuel. The amount of fuel that is used during the entire flight. From brake release at the departure area, takeoff and to landing at the destination.

C-rate. A scale of charge and discharge rates of batteries. For example, a 1C rate means that the discharge current will empty the battery within 1 hour, 0.5C rate means that the discharge current will empty the battery within 2 hours.

Cruise. The phase during flight when an aircraft has reached its level of altitude between climb and descend.

DC bus. A direct current busbar, which is a collection of conductors transmitting on a single metal bar.

Dendrites. Small, tree-like formation from a metal that can grow inside the cells of a battery. They can trigger failure, short circuit or a fire.

Empty weight. The weight of an aircraft without passengers, luggage (and cargo), and fuel, but includes fuel that is unusable to drain, full engine oil, and full operating liquids.

FAA. The federal aviation authorities in United States (USA).

Final reserve fuel. The minimum amount of fuel that is required to fly for 30 minutes at 1 500 feet above an aerodrome.

Glider. Aircraft that can fly without an engine by gliding.

H_E. The degree of hybridisation of the energy source.

H_P. The degree of hybridisation of the power source.

Holding fuel. The amount of fuel that an aircraft needs to fly for a period of time calculated at the holding fuel consumption rate assumed for the aircraft for the operational conditions.

Inverter. An electric device that transforms direct current to alternate current.

Jet A-1 fuel / jetfuel. Fossil fuel used for aircraft.

Landing distance. The length for an aircraft to make a complete stop after crossing the runway threshold at 15 meters (50 feet) altitude.

Load. The extra mass stored on an aircraft, such as passengers and luggage.

Minimum takeoff fuel. Equals off block fuel minus taxi fuel.

Off block fuel. The total amount of fuel required for the entire journey of a flight.

Payload weight. The amount of external weight an aircraft can handle: Passengers, crew, cargo and luggage.

Rate of climb. An aircraft's change in altitude measured in feet per minute.

Retrofit. To furnish an existing object with new modified parts or equipments.

Service Ceiling. The maximum altitude an aircraft is designed to withstand.

Takeoff mass - T/O mass. The maximum weight an aircraft is alloved to withstand for takeoff.

Takeoff distance. The length of ground run and the distance from where the landing gears leave the ground until aircraft reach 15 meter (50 feet) altitude.

Taxi fuel. The amount of fuel that is used before takeoff.

Thermal runaway. A state when an internal source of heat leads to an increase in temperature for a battery. It can lead to an ignition, which can further result in an explosion.

Transit flight. A flight that reaches its final destination through two or more flights.

True airspeed. The equivalent velocity of an aircraft adjusted for air density, and relative for the air it's flying through.

Turnaround. The time period between when an aircraft has landed and it departs from an airport.

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Attachment 1

Samset, Ivar

to. 23.01.2020 15:09

Til: Sunniva Petersen Jikiun

Hei!

Jeg har trafikktallene for de tre siste årene mellom Bergen og Stavanger:

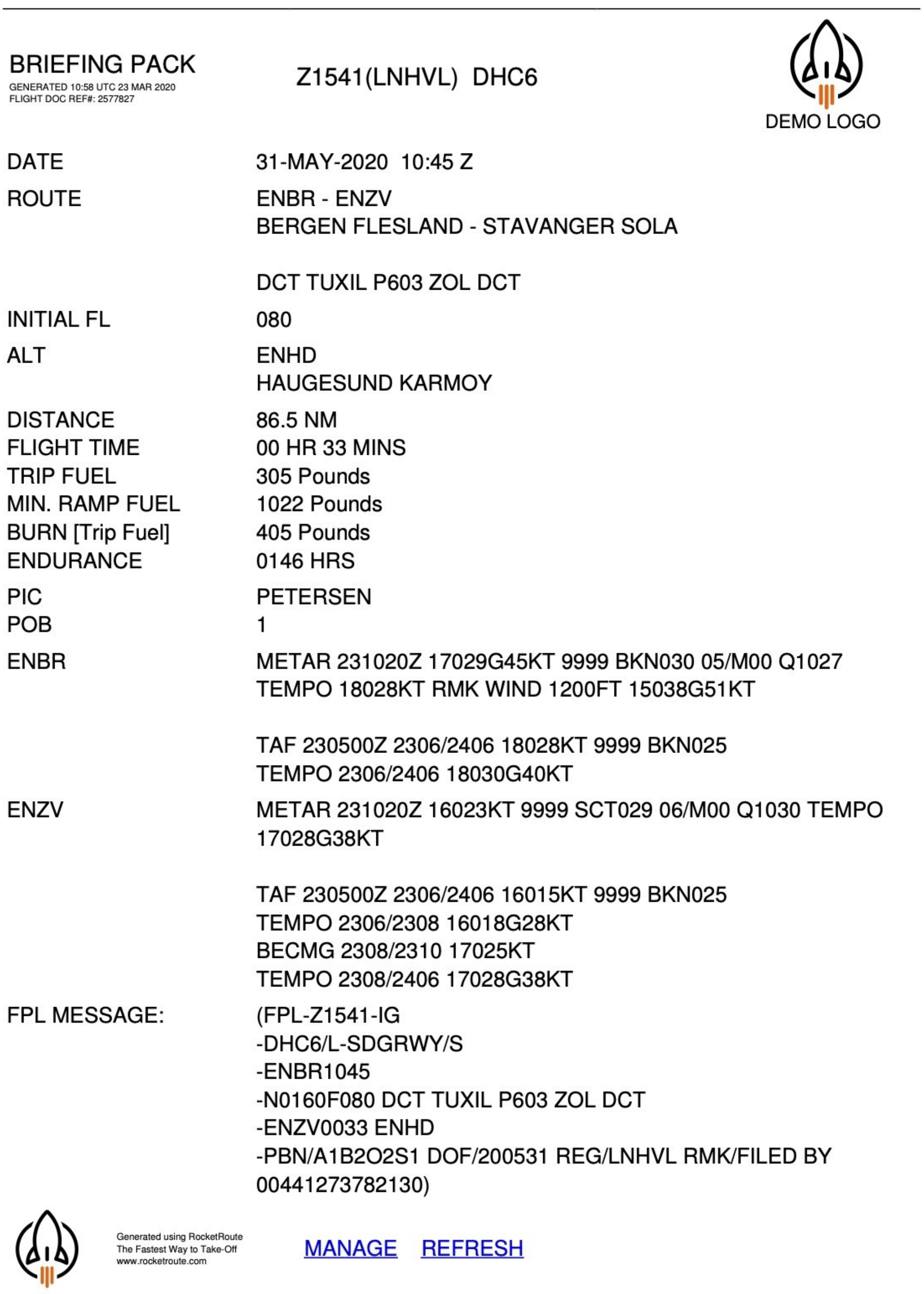
2019	510.508
2018	492.816
2017	486.017

Håper det er dette du trenger. Dersom det er mer du trenger, er det bare å ta kontakt, men jeg har dessverre ikke tall for lenger tilbake i tid.

Vennlig hilsen
Ivar Samset
administrasjonsleder
Bergen lufthavn, Flesland

AVINOR

Attachment 2



BRIEFING PACK
GENERATED 10:58 UTC 23 MAR 2020
FLIGHT DOC REF#: 2577827

Z1541(LNHVL) DHC6

DEMO LOGO

DATE	31-MAY-2020 10:45 Z
ROUTE	ENBR - ENZV BERGEN FLESLAND - STAVANGER SOLA DCT TUXIL P603 ZOL DCT
INITIAL FL	080
ALT	ENHD HAUGESUND KARMOY
DISTANCE	86.5 NM
FLIGHT TIME	00 HR 33 MINS
TRIP FUEL	305 Pounds
MIN. RAMP FUEL	1022 Pounds
BURN [Trip Fuel]	405 Pounds
ENDURANCE	0146 HRS
PIC	PETERSEN
POB	1
ENBR	METAR 231020Z 17029G45KT 9999 BKN030 05/M00 Q1027 TEMPO 18028KT RMK WIND 1200FT 15038G51KT TAF 230500Z 2306/2406 18028KT 9999 BKN025 TEMPO 2306/2406 18030G40KT
ENZV	METAR 231020Z 16023KT 9999 SCT029 06/M00 Q1030 TEMPO 17028G38KT TAF 230500Z 2306/2406 16015KT 9999 BKN025 TEMPO 2306/2308 16018G28KT BECMG 2308/2310 17025KT TEMPO 2308/2406 17028G38KT
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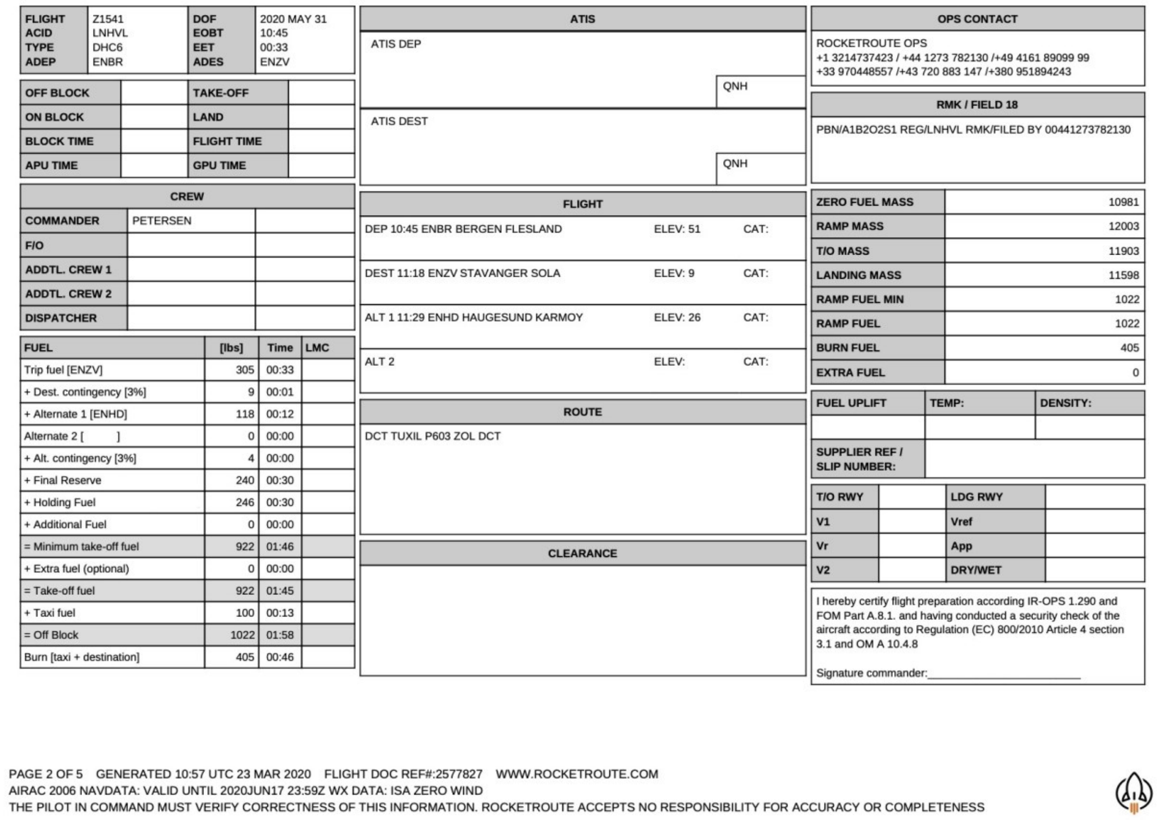

FLIGHT **ACID** **TYPE** **ADEP**	Z1541 LNHVL DHC6 ENBR	**DOF** **EOBT** **EET** **ADES**	2020 MAY 31 10:45 00:33 ENZV

OFF BLOCK		**TAKE-OFF**	
ON BLOCK		**LAND**	
BLOCK TIME		**FLIGHT TIME**	
APU TIME		**GPU TIME**	

CREW		
COMMANDER	PETERSEN	
F/O		
ADDTL. CREW 1		
ADDTL. CREW 2		
DISPATCHER		

FUEL	**[lbs]**	**Time**	**LMC**
Trip fuel [ENZV]	305	00:33	
+ Dest. contingency [3%]	9	00:01	
+ Alternate 1 [ENHD]	118	00:12	
Alternate 2 [ ]	0	00:00	
+ Alt. contingency [3%]	4	00:00	
+ Final Reserve	240	00:30	
+ Holding Fuel	246	00:30	
+ Additional Fuel	0	00:00	
= Minimum take-off fuel	922	01:46	
+ Extra fuel (optional)	0	00:00	
= Take-off fuel	922	01:45	
+ Taxi fuel	100	00:13	
= Off Block	1022	01:58	
Burn [taxi + destination]	405	00:46	

ATIS

ATIS DEP

QNH

ATIS DEST

QNH

FLIGHT

DEP 10:45 ENBR BERGEN FLESLAND	ELEV: 51	CAT:
DEST 11:18 ENZV STAVANGER SOLA	ELEV: 9	CAT:
ALT 1 11:29 ENHD HAUGESUND KARMOY	ELEV: 26	CAT:
ALT 2	ELEV:	CAT:

ROUTE

DCT TUXIL P603 ZOL DCT

CLEARANCE

OPS CONTACT

ROCKETROUTE OPS
+1 3214737423 / +44 1273 782130 /+49 4161 89099 99
+33 970448557 /+43 720 883 147 /+380 951894243

RMK / FIELD 18

PBN/A1B2O2S1 REG/LNHVL RMK/FILED BY 00441273782130

ZERO FUEL MASS	10981
RAMP MASS	12003
T/O MASS	11903
LANDING MASS	11598
RAMP FUEL MIN	1022
RAMP FUEL	1022
BURN FUEL	405
EXTRA FUEL	0

FUEL UPLIFT	**TEMP:**	**DENSITY:**
SUPPLIER REF / SLIP NUMBER:		

T/O RWY		**LDG RWY**	
V1		**Vref**	
Vr		**App**	
V2		**DRY/WET**	

I hereby certify flight preparation according IR-OPS 1.290 and FOM Part A.8.1. and having conducted a security check of the aircraft according to Regulation (EC) 800/2010 Article 4 section 3.1 and OM A 10.4.8

Signature commander:________________________

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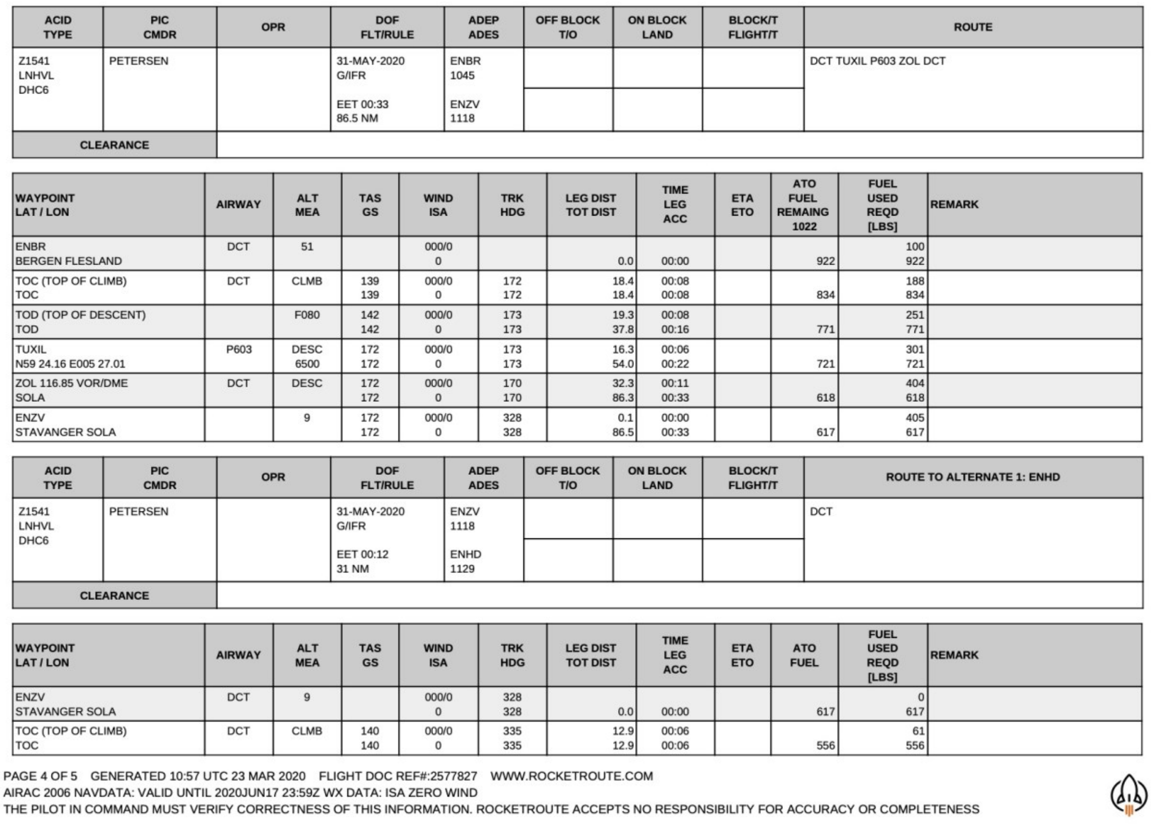
AIRAC 2006 NAVDATA: VALID UNTIL 2020JUN17 23:59Z WX DATA: ISA ZERO WIND
THE PILOT IN COMMAND MUST VERIFY CORRECTNESS OF THIS INFORMATION. ROCKETROUTE ACCEPTS NO RESPONSIBILITY FOR ACCURACY OR COMPLETENESS



ACID TYPE	PIC CMDR	OPR	DOF FLT/RULE	ADEP ADES	OFF BLOCK T/O	ON BLOCK LAND	BLOCK/T FLIGHT/T	ROUTE
Z1541 LNHVL DHC6	PETERSEN		31-MAY-2020 G/IFR	ENBR 1045				DCT TUXIL P603 ZOL DCT
			EET 00:33 86.5 NM	ENZV 1118				
CLEARANCE								

WAYPOINT LAT / LON	AIRWAY	ALT MEA	TAS GS	WIND ISA	TRK HDG	LEG DIST TOT DIST	TIME LEG ACC	ETA ETO	ATO FUEL REMAING 1022	FUEL USED REQD [LBS]	REMARK
ENBR BERGEN FLESLAND	DCT	51		000/0 0		0.0	00:00		922	100 922	
TOC (TOP OF CLIMB) TOC	DCT	CLMB	139 139	000/0 0	172 172	18.4 18.4	00:08 00:08		834	188 834	
TOD (TOP OF DESCENT) TOD		F080	142 142	000/0 0	173 173	19.3 37.8	00:08 00:16		771	251 771	
TUXIL N59 24.16 E005 27.01	P603	DESC 6500	172 172	000/0 0	173 173	16.3 54.0	00:06 00:22		721	301 721	
ZOL 116.85 VOR/DME SOLA	DCT	DESC	172 172	000/0 0	170 170	32.3 86.3	00:11 00:33		618	404 618	
ENZV STAVANGER SOLA		9	172 172	000/0 0	328 328	0.1 86.5	00:00 00:33		617	405 617	

ACID TYPE	PIC CMDR	OPR	DOF FLT/RULE	ADEP ADES	OFF BLOCK T/O	ON BLOCK LAND	BLOCK/T FLIGHT/T	ROUTE TO ALTERNATE 1: ENHD
Z1541 LNHVL DHC6	PETERSEN		31-MAY-2020 G/IFR	ENZV 1118				DCT
			EET 00:12 31 NM	ENHD 1129				
CLEARANCE								

WAYPOINT LAT / LON	AIRWAY	ALT MEA	TAS GS	WIND ISA	TRK HDG	LEG DIST TOT DIST	TIME LEG ACC	ETA ETO	ATO FUEL	FUEL USED REQD [LBS]	REMARK
ENZV STAVANGER SOLA	DCT	9		000/0 0	328 328	0.0	00:00		617	0 617	
TOC (TOP OF CLIMB) TOC	DCT	CLMB	140 140	000/0 0	335 335	12.9 12.9	00:06 00:06		556	61 556	

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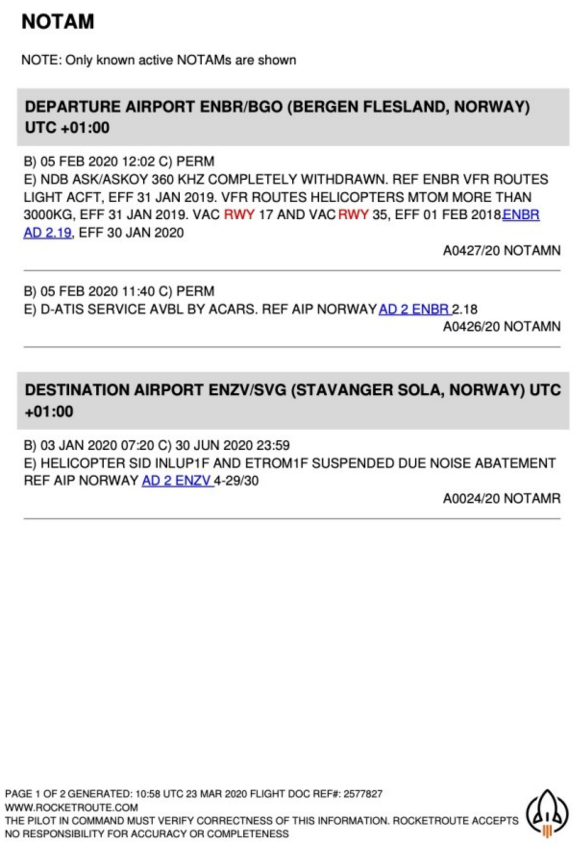

NOTAM

NOTE: Only known active NOTAMs are shown

DEPARTURE AIRPORT ENBR/BGO (BERGEN FLESLAND, NORWAY) UTC +01:00

B) 05 FEB 2020 12:02 C) PERM
E) NDB ASK/ASKOY 360 KHZ COMPLETELY WITHDRAWN. REF ENBR VFR ROUTES LIGHT ACFT, EFF 31 JAN 2019. VFR ROUTES HELICOPTERS MTOM MORE THAN 3000KG, EFF 31 JAN 2019. VAC RWY 17 AND VAC RWY 35, EFF 01 FEB 2018 ENBR AD 2.19, EFF 30 JAN 2020
A0427/20 NOTAMN

B) 05 FEB 2020 11:40 C) PERM
E) D-ATIS SERVICE AVBL BY ACARS. REF AIP NORWAY AD 2 ENBR 2.18
A0426/20 NOTAMN

DESTINATION AIRPORT ENZV/SVG (STAVANGER SOLA, NORWAY) UTC +01:00

B) 03 JAN 2020 07:20 C) 30 JUN 2020 23:59
E) HELICOPTER SID INLUP1F AND ETROM1F SUSPENDED DUE NOISE ABATEMENT REF AIP NORWAY AD 2 ENZV 4-29/30
A0024/20 NOTAMR

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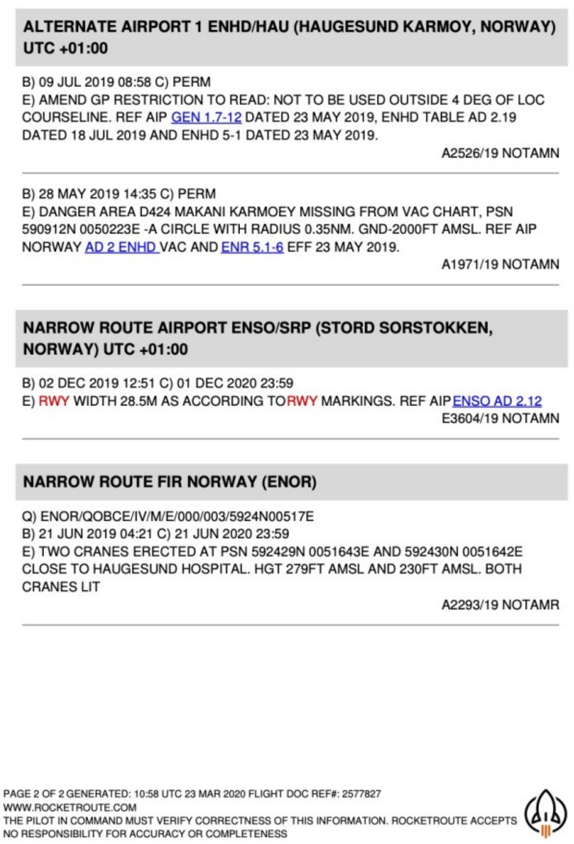

ALTERNATE AIRPORT 1 ENHD/HAU (HAUGESUND KARMOY, NORWAY) UTC +01:00

B) 09 JUL 2019 08:58 C) PERM
E) AMEND GP RESTRICTION TO READ: NOT TO BE USED OUTSIDE 4 DEG OF LOC COURSELINE. REF AIP GEN 1.7-12 DATED 23 MAY 2019, ENHD TABLE AD 2.19 DATED 18 JUL 2019 AND ENHD 5-1 DATED 23 MAY 2019.
A2526/19 NOTAMN

B) 28 MAY 2019 14:35 C) PERM
E) DANGER AREA D424 MAKANI KARMOEY MISSING FROM VAC CHART, PSN 590912N 0050223E -A CIRCLE WITH RADIUS 0.35NM. GND-2000FT AMSL. REF AIP NORWAY AD 2 ENHD VAC AND ENR 5.1-6 EFF 23 MAY 2019.
A1971/19 NOTAMN

NARROW ROUTE AIRPORT ENSO/SRP (STORD SORSTOKKEN, NORWAY) UTC +01:00

B) 02 DEC 2019 12:51 C) 01 DEC 2020 23:59
E) RWY WIDTH 28.5M AS ACCORDING TO RWY MARKINGS. REF AIP ENSO AD 2.12
E3604/19 NOTAMN

NARROW ROUTE FIR NORWAY (ENOR)

Q) ENOR/QOBCE/IV/M/E/000/003/5924N00517E
B) 21 JUN 2019 04:21 C) 21 JUN 2020 23:59
E) TWO CRANES ERECTED AT PSN 592429N 0051643E AND 592430N 0051642E CLOSE TO HAUGESUND HOSPITAL. HGT 279FT AMSL AND 230FT AMSL. BOTH CRANES LIT
A2293/19 NOTAMR

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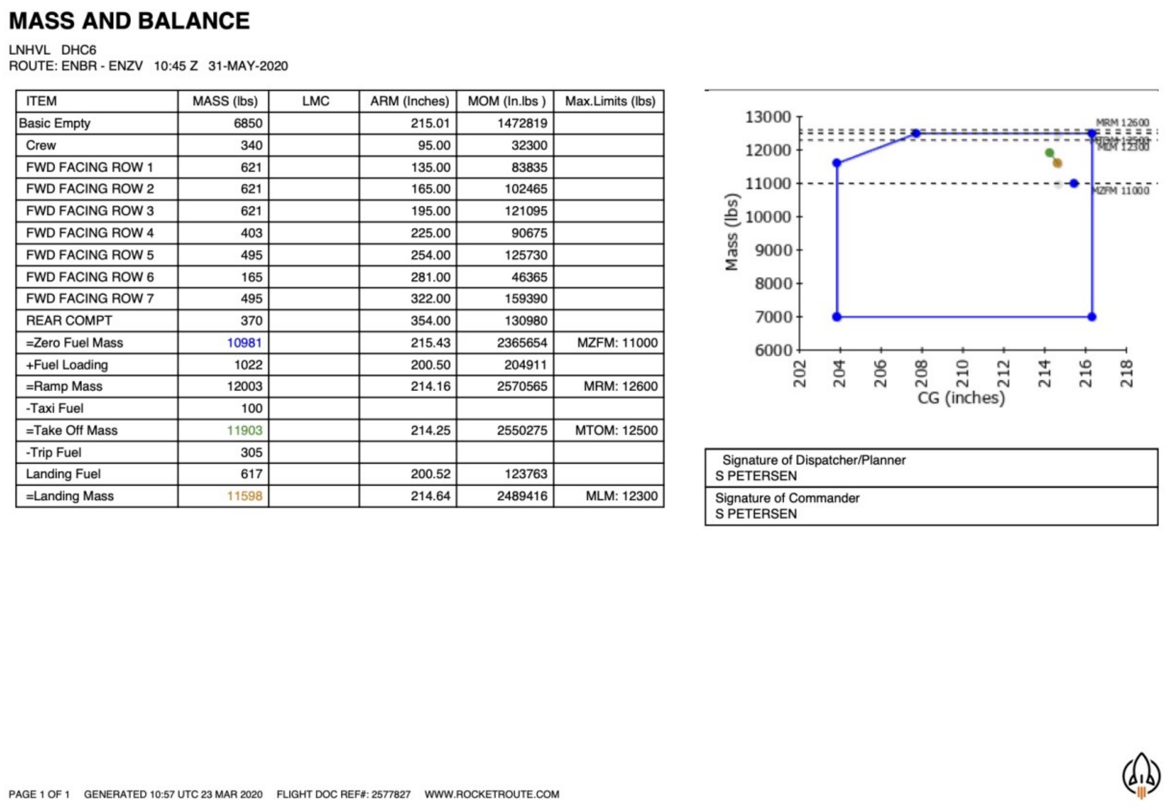

MASS AND BALANCE

LNHVL DHC6
ROUTE: ENBR - ENZV 10:45 Z 31-MAY-2020

ITEM	MASS (lbs)	LMC	ARM (Inches)	MOM (In.lbs)	Max.Limits (lbs)
Basic Empty	6850		215.01	1472819	
Crew	340		95.00	32300	
FWD FACING ROW 1	621		135.00	83835	
FWD FACING ROW 2	621		165.00	102465	
FWD FACING ROW 3	621		195.00	121095	
FWD FACING ROW 4	403		225.00	90675	
FWD FACING ROW 5	495		254.00	125730	
FWD FACING ROW 6	165		281.00	46365	
FWD FACING ROW 7	495		322.00	159390	
REAR COMPT	370		354.00	130980	
=Zero Fuel Mass	10981		215.43	2365654	MZFM: 11000
+Fuel Loading	1022		200.50	204911	
=Ramp Mass	12003		214.16	2570565	MRM: 12600
-Taxi Fuel	100				
=Take Off Mass	11903		214.25	2550275	MTOM: 12500
-Trip Fuel	305				
Landing Fuel	617		200.52	123763	
=Landing Mass	11598		214.64	2489416	MLM: 12300

Signature of Dispatcher/Planner S PETERSEN
Signature of Commander S PETERSEN

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