Energy transition for the global aviation industry – a review of alternative aircraft propulsion

Master’s Thesis

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Submission date: 22.05.2019
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Abstract

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Title: Energy transition for the global aviation industry – a review of alternative aircraft propulsion
Year: 2019
Place: Lappeenranta
Type: Master's thesis, Lappeenranta University of Technology, School of Engineering Science, Global Management of Innovation and Technology
Content: 107 pages, 57 figures and 11 tables
Supervisors: Adj. Professor Kalle Elfvengren, Professor Christian Breyer
Keywords: Alternative aircraft propulsion, Levelized cost of Mobility (LCOM), fossil jet fuel, biofuels, synthetic fuels, electric aviation, liquid hydrogen, zero emission aviation

Aviation emission from fossil fuel-based combustion engines are adversely contributing to global climate change. Based on the 2015 Paris Agreement of limiting global warming to 1.5°C, zero Greenhouse Gases (GHG) are to be emitted by 2050. While aircraft propulsion and aerodynamics technology improvements are achieved, aviation growth and related GHG emissions are outpacing these by 2.5% per year. Continuing the business-as-usual scenario leads to a significant emission gap by 2050. In this thesis, alternative aircraft propulsion concepts such as bio- and synthetic fuels, electric aircraft and liquid hydrogen fuelled aircraft are demonstrated and compared based on assorted criteria.

The research methods applied are a quantitative comparison by Levelized Cost of Mobility (LCOM), as well as a qualitative technology selection by Analytic Hierarchy Process (AHP). From a cost perspective, bio- and synthetic fuels are to reduce emission of aviation on short term once carbon costs increase. By 2020, kerosene fuelled combustion engines remain the least cost option. By 2035, first all-electric aircraft with zero emission are ready to be deployed on regional and short routes, however, they are infeasible with current and projected future battery densities on routes >1667 km. From 2050 on, liquid-hydrogen aircraft with close to zero emissions can contribute to lowering GHG emissions, especially on long ranges. Following overall sustainability criteria such as cost, emission, readiness and safety, electric propulsion is the most recommended option to close the emission gap of aviation, followed by bio- and synthetic fuels and hydrogen fuelled aviation.
Acknowledgements

First, I would like to thank my supervisors Kalle and Christian for their great support, guidance and funding. I very much appreciate providing me with this personally meaningful and fascinating topic. Only with your aid this thesis project could be successfully accomplished.

A big thank you goes also to my beloved family, friends, study colleagues and of course Rasse. I am fortunate that I could count on your unlimited motivation and honest feedback at every time.

Lisa Marie Meier
Lappeenranta, 22.05.2019
“Future scenarios for emission trends and the global aspirational goal of keeping the net CO\textsubscript{2} emissions at 2020 level result in a gap of 1,039 Mt CO\textsubscript{2} in 2050.”

International Civil Aviation Organization, 2016

"Electric flying is becoming a reality and we can now foresee a future that is not exclusively dependent on jet fuel.”

Johan Lundgren, 2018 – CEO of easyJet

“All-electric aircraft with 180 passengers are likely infeasible with current battery technology.”

Albert R. Gnadt et.al, 2019 – Massachusetts Institute of Technology

“When I was flying around the world in my solar airplane, there was no noise, no pollution, no fuel... and I could fly forever.”

Bertrand Piccard, 2015 – pilot on Solar Impulse

“If commercial aviation were to get 6% of its fuel supply from biofuel by 2020, the industry’s overall carbon footprint would reduce by 5% – in two years’ time.”

Neste Corporation, 2018

“Hydrogen has been confirmed as offering a chance of continuing long-term growth of aviation without damaging the atmosphere.”

European Commission, 2003
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<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>AHP</td>
<td>Analytic Hierarchy Process</td>
</tr>
<tr>
<td>APU</td>
<td>Auxiliary Power Unit</td>
</tr>
<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
</tr>
<tr>
<td>ATJ</td>
<td>Alcohol to Jet</td>
</tr>
<tr>
<td>CAEP</td>
<td>Committee on Aviation Environmental Protection</td>
</tr>
<tr>
<td>Capex</td>
<td>Capital Expenditure</td>
</tr>
<tr>
<td>COP</td>
<td>Conference of Parties</td>
</tr>
<tr>
<td>CORSIA</td>
<td>Carbon Offsetting and Reduction Scheme for International Aviation</td>
</tr>
<tr>
<td>Crf</td>
<td>Capital Recovery Factor</td>
</tr>
<tr>
<td>CSP</td>
<td>Concentrated Solar Power</td>
</tr>
<tr>
<td>DSHC</td>
<td>Direct Sugars to Hydrocarbons</td>
</tr>
<tr>
<td>ETS</td>
<td>Emissions Trading System</td>
</tr>
<tr>
<td>FT</td>
<td>Fischer-Tropsch</td>
</tr>
<tr>
<td>GHG</td>
<td>Greenhouse Gases</td>
</tr>
<tr>
<td>HEFA</td>
<td>Hydroprocessed Esters and Fatty Acids</td>
</tr>
<tr>
<td>HTL</td>
<td>Hydrothermal Liquefaction</td>
</tr>
<tr>
<td>IATA</td>
<td>International Air Transport Association</td>
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<tr>
<td>ICAO</td>
<td>International Civil Aviation Organization</td>
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<tr>
<td>I/LUC</td>
<td>Indirect / Direct Land Use Change</td>
</tr>
<tr>
<td>IPCC</td>
<td>International Panel on Climate Change</td>
</tr>
<tr>
<td>LCOE</td>
<td>Levelized Cost of Electricity</td>
</tr>
<tr>
<td>LCOM</td>
<td>Levelized Cost of Mobility</td>
</tr>
<tr>
<td>NDC</td>
<td>Nationally Determined Contribution</td>
</tr>
<tr>
<td>Opex</td>
<td>Operational Expenditure</td>
</tr>
<tr>
<td>Pkm</td>
<td>Passenger Kilometre</td>
</tr>
<tr>
<td>QFD</td>
<td>Quality Function Deployment</td>
</tr>
<tr>
<td>WACC</td>
<td>Weighted Average Cost of Capital</td>
</tr>
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</table>
1. Introduction

Climate change is a major threat to the human society in the form of increasing global average temperatures, rising sea levels, more frequent extreme weather periods and loss of biodiversity (IPCC, 2014, p. 6). Emissions of global aviation are responsible of 2% of man-made global warming and the sector is experiencing a steep growth of 4.5% every year (Airbus, 2018, p. 34; Boeing, 2018, p. 39; IEA, 2018b). Since centuries, mankind urges to fly. Aviation is representing, besides spatial activities, the most advanced and complex mode of transport for people and goods. Hence, technological advancements are challenging to realize due to exceptional design requirements concerning safety, weight, cost, noise and emissions.

Yet, upcoming threats such as climate change, have made ground-breaking development of new technologies necessary. Since the world community signed the Paris Climate Agreement in 2015, climate change has become the prevailing challenge for designing future aircraft and propulsion technology. In order to “strengthen the global response to the threat of climate change”, the global temperature increase is agreed to be limited to 1.5°C in 2050 compared to 1990 levels. In 2018, the International Panel on Climate Change (IPCC) assessed specific impacts of Greenhouse Gas (GHG) emissions as primary cause for global climate change. The panel concludes that the world community is obliged to reach a scenario of zero emissions by 2050 throughout all sectors (Kromp-Kolb, 2014, p. 14). Despite the Conference of Parties 21 (COP) did not specify emissions targets for the global aviation sector, all sectors remain responsible to perform efforts that limit global warming. This responsibility is clearly including the aviation sector. Hence, the energy transition of the aviation sector focussing on energy consumption and GHG emissions is crucial.

The key driver for increasing energy demand and linked rising CO₂ emissions is population growth (Kaya and Yokobori, 1997, p. 273). Regarding aviation, this growth in combination with human development advances leads to an increase in global aviation. Global revenue kilometres per passenger are expected to rise by ca. 4.5% (Airbus, 2018, p. 9; Boeing, 2018,
Air traffic is projected to double by 2032 and to triple by 2050 based on 2018 volume (Gnadt et al., 2019, p. 1).

From this trend, airlines cannot only benefit commercially, but likewise contribute to sustainable development by providing infrastructure for connecting people around the world. On the contrary, airlines face increasing pressure to lower their carbon emissions. Without addressing efforts to reduce the growth-related GHG emissions, the industry may contribute to 22% of global emissions in 2050 which is in severe conflict with the zero emission agreement in the course of the Paris Agreement (Cames et al., 2015, p. 40).

International Civil Aviation Organisation (ICAO) anticipates that a 1,039 Mt gap of CO₂ emissions by 2050 is required to be closed. With growing total flights particularly in the developing countries it is crucial to discuss and decide preventive actions to limit GHG emissions (Yilmaz and Atmanli, 2017, p. 1378). Overcoming this strife is unlikely to be achieved by limiting aviation growth, related jobs and mobility of people, but by promptly detecting feasible alternatives to current aircrafts fossil-based propulsion. The aim of this thesis is to discuss cost-oriented means that limit impacts on the environment of aviation in the largest possible extent. Thereby, alternative aircraft propulsion technology is demonstrated and systematically compared. Reviewing technically feasible and cost-

Figure 1: CO₂ emission trends from international aviation (ICAO, 2016a, p. 17)
competitive sustainable propulsion solutions applicable in the near and distant future is a substantial approach directing towards the accomplishment of zero emission targets at continuing growth of global air travel.

1.1. Background

Aviation growth is projected to outpace propulsion technology advancements and aircraft efficiency enhancement. Since the world community agreed on the 1.5°C goals of the Paris agreement, all countries and sectors are assigned to contribute their share to global emission reduction. In the aviation sector, aspirational goals have been set and several recent legislative frameworks have been implemented. As consequence, research activity in alternative aircraft propulsion has experienced a steep growth in the previous years. Nonetheless, a review of possible alternatives to kerosene-based aviation including a recommendation for decision makers is missing. Thus, this study helps airlines and investors to strategically decide on a specific future aircraft concept and related infrastructure changes.

Paris Agreement

Climate change is one of the most dramatic challenges humanity must overcome in the 21st century. Therefore, member states of the United Nations Climate Change Conference agreed in Paris on the 21st summit of the COP to take ambitious actions to react on climate change. The central aim is to keep the global temperature increase well below 2°C and targeting 1.5°C. Various working groups translated this aim into exact adaptation and mitigation goals for specific regions and sectors. Until May 2019, 185 countries ratified the Paris agreement which signifies the consent of a country to be bound to a treaty (Vienna Convention, 1969, pp. 335–336). By adopting Nationally Determined Contributions (NDCs) sectoral GHG emission reduction targets are set. Sectors with highest contribution to global warming are responsible to mitigate climate change first. The global GHG emissions by sector in 2014 are the following:
The energy, transport and industry sector account for the largest part of manmade GHG emissions. Besides that, the aviation sector accounts for 2.6% of global manmade emissions with growth prospects. First actions have been taken in the energy sector by a comprehensive energy transition from fossil fuel-based energy resources, such as coal and oil towards gaining electricity and heat from renewable energy resources. The industry sector is starting to reduce its emissions by demand-side measures, energy-efficiency improvements, electrification of heat and hydrogen usage (Pee et al., 2018, p. 25). The subsequent sector accepting responsibility is the transport sector. Modern highway-capable hybrid and electric cars were initially manufactured two decades ago and are entering global markets. Moreover, investments in public transport systems are made in order to reduce road traffic. Likewise, other parts of the transportation sector are due to limit emissions in the near future, among them the aviation sector.

**Aviation Market Development**

Numerous cost saving approaches are continuously performed by airlines and have successfully reduced fuel savings and thereby reductions in emissions. Nonetheless, these and similar emission reduction efforts are insufficient regarding the projected steep growth scenario of the industry for the coming decades. Furthermore, global oil supply is expected to peak around 2020 (Bentley, 2016, p. 72). Regarding the elongated lead-times of new aircraft and propulsion development and type certification, the consideration of alternatives to kerosene becomes urgent.

Per year, aircraft propulsion and aerodynamics technology improves and thus heightens the fleet efficiency of by 2% in average (Schäfer et al., 2016, p. 3; Gnadt et al., 2019, p. 1).
However, this positive contribution to lowering total emissions is outpaced by an average annual growth of 4.5% in aviation activities. The projected growth of different regions of the world can be found in the figure below.

![Map showing aviation market growth by region](image)

*Figure 3: Aviation market growth by region, adapted from (Airbus, 2018, p. 34; Boeing, 2018, p. 39)*

Especially developing countries are expected to grow more than 5% annually. Whereas the growth projection for Europe and North America is more conservative, it is yet outpacing expected efficiency improvements.

Annually, around 371 billion litres of kerosene are consumed globally and since 1980 this amount has been rising by 3.6% every year (Epstein and O’Flarity, 2019, p. 2). The largest part of jet fuel is consumed by commercial single-aisle, such as Boeing 737 and Airbus A320 and twin-aisle aircraft types such as Boeing 777 and Airbus A330.

![Fuel consumption by aircraft type](image)

*Figure 4: Fuel consumption by aircraft type, adapted from (Yutko and Hansman, 2011, p. 44)*
Taken together, these types of aircraft consume 93% of the world’s kerosene. Regional jets and turboprops and business jets consume only insignificant amounts of jet fuel (5% and ca. 1% respectively). Common ranges flown by aircraft class are 1292 km by small single-aisle aircraft with less than 150 seats, 2039 km by large single-aisle aircraft with more than 150 seats and 6570 km by twin-aisle aircraft (MIT, 2018). Regarding total passenger kilometres (pkm), routes under 2000 km represent 77% of the most frequented routes. Regardless of this development, emissions from long range aircraft are taking a larger share of 57% than short range aircraft (Epstein and O’Flarity, 2019, p. 2). When categorizing aircraft by its GHG emissions, all aircraft heavier than 25 t consume 98% of global kerosene (Epstein and O’Flarity, 2019, p. 1). Hence, this study is focussing on common regional, single-aisle and twin-aisle aircraft.

When considering emission from aviation, mainly passenger transport is of interest for most stakeholders. However, air cargo is contribution with 9% of global airline’s revenues (IATA, 2018b, p. 3). In 2017, 223,730 freight ton kilometres have been accounted globally (ICAO, 2018, p. 1). Air cargo is transported around half by passenger aircraft and half by specific freighter aircraft. Also for freighter aircraft, traffic growth is expected to increase until 2037 around 3.8% per year (Airbus, 2018, p. 128; Boeing, 2018, p. 27). Nonetheless, compared to 7,699,420 pkm registered which results in 97.11% of global aviation, the share of freight transport is marginal and will not be further discussed. It is assumed that the recommended challenges and decisions taken are applied to both passenger and freight transport likewise.

Besides decarbonizing the aviation sector, also activity in other types of transport needs to be considered. International Air Transport Association’s (IATA) future scenario study predicts that short range, domestic routes may be taken over by high-speed trains (IATA, 2018a, p. 32). Likewise, German train operator Deutsche Bahn recently inaugurated a new high-speed connection on the most frequent domestic route (Neumann, 2017). The company expects to increase their market share on this route from 15-20% to 40%, which is significant regarding the amount of traffic of 974.4 million pkm. Similar projects are under construction in India, Japan and Iran. Moreover, new technology, such as hyperloop, drone companies and VTOL may take activity from airlines and simultaneously reduce GHG emissions once their operation is proven to be viable (IATA, 2018a, p. 32).
Overall, continuous efficiency enhancements of aircraft and airline operations let the kerosene consumption rise slower than annual traffic growth. However, from the background of a zero-emission target for 2050, this trend needs to reverse within the next 30 years.

Environmental Legislation in Aviation

Some scholars recognize market based measures, such as emission trading schemes (ETS), necessary and capable of reducing aviation emissions significantly (Lee, et al., 2013, p. 13). The two main market-based measures for aviation are the EU ETS and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA). In 2012, the EU ETS was amended to apply also for emissions from aviation. All flights from, to and within the European Economic Area are included and the scheme is valid for both EU and non-EU based airlines. Initially, also non-domestic flights starting or landing within the EEA were in the scope of the EU ETS, but from 2012 to 2023 the requirements were intermitted in order to facilitate ICAO’s efforts to establish CORSIA (EC, 2019). Overall, including aviation into EU ETS did not reach the aimed impact of the scheme on aviation emissions due to oversupply of allowances and thus too low carbon prices (T&E, 2016, p. 14).

In 2016, CORSIA was introduced in order to address international aviation emissions. This scheme was developed according to the overall target of carbon neutral growth from 2020 on and stipulates carbon offsetting requirements for any emission exceeding the reference level (ICAO, 2016a, p. 145). The concept of compensating emissions through offsetting was decided through ICAO as technology and economics today would not consistently allow significant emission reduction in a short time frame (ICAO, 2016a, p. 146).

![Figure 5: Phases of CORSIA scheme, adapted from (Scheelhaase et al., 2018, p. 57)](image)
The pilot phase from 2021 to 2023 and the first phase from 2024 to 2026 are voluntary and only from the second phase on (2027-2035) the scheme becomes boundary for all states. As of May 2019, 80 states participate voluntary in the pilot phase (ICAO, 2019). In case the offsets are accomplished in addition to in-house emission reductions, a positive effect on the climate on a global scale is reached. Nevertheless, the phase-in implementation of CORSIA demonstrates only small positive effect on aviation emissions for at least another ten years (O’Connell et al., 2019, p. 506).

Overall, aviation stakeholders must comply with local government’s ambitious climate, GHG emission, noise pollution and energy targets. For example, the EU implemented the Environmental Noise Directive and Balanced Approach Regulation as legislations in order to monitor environmental noise pollution and based on which actions can be taken (EEA, 2016, p. 10). Concerning air quality, ICAO’s Committee on Aviation Environmental Protection (CAEP) is responsible for ensuring aircraft engine emissions standards which were first established in 1981. EU legislation was formed based on these standards (EEA, 2016, p. 27). Moreover, the Aviation Strategy for Europe underlines the need for contribution of research and development activities for innovative and environmental friendly technologies in order to reduce aviation’s environmental impacts (EC, 2015, p. 13).

1.2. Objectives and Scope

The objective of this master’s thesis is to analyse how the energy transition in the aviation sector towards low-carbon air transport can be accomplished. The main aim is to evaluate and recommend an alternative solution to commonly deployed fossil fuelled combustion engine driven aircraft.

Research questions

In order to accomplish the research objective, the following research questions will be discussed and answered.

1) What kind of aircraft propulsion technology is recommended to be commercially used by air carriers in the future in order to achieve the 1.5°C constraint?
   a) What type of alternative aircraft propulsion is generally qualified to act as replacement of fossil fuel driven combustion engines?
b) Which alternative aircraft propulsion represents the lowest Levelized Cost of Mobility for which operational route range?

c) What is the set of qualitative criteria determining a justified choice of alternative aircraft propulsion?

d) Which alternative aircraft propulsion is to be chosen according to numerous qualitative criteria?

**Keywords for literature review**

Previous literature offers a wide range of concepts and substitutes for conventional fossil fuel-based aviation. Major keywords for the literature review are alternative aircraft propulsion, LCOM, fossil jet fuel, biofuels, synthetic fuels, electric aviation, liquid hydrogen and zero emission aviation. Moreover, each cluster of the literature review has various sub-keywords that are presented in the following mind-map.

*Figure 6: Keywords for literature review*
Based on the aggregate of these keywords the following chapter provide an overview about concepts and previous results on energy transition in the aviation sector.

**Limitations**

Reducing GHG emissions of aviation can be reached by improving multiple aspects in the categories airframe design, propulsion systems, air traffic management as well as airline operations. Similarly, the sector’s environmental targets are clustered in these categories such as in Vision 2020 and AGAPE 2020 (Muller, 2010). In order to limit the scope for this thesis, the focus lays on GHG emission reduction potential by alternative propulsion technology. Nonetheless, further research activity is recommended in order to promote and accomplish emission reduction possibility from all above-mentioned categories.

Especially detailed technological specification of possible alternative propulsion solutions and any improvement of engine propulsion technology are excluded. Moreover, any detailed beneficial or required aircraft body, propulsion structure, aerodynamics and structural changes or proposals for changes are not part of this thesis. The focus of this work lays on the overall sustainable feasibility of the alternative propulsion technology, its GHG emission reduction potential and the cost of implementing the technology from an airline perspective. Furthermore, the readiness of production, infrastructure and supply as well as sustainability criteria are discussed, and the solutions are compared by means of a structured technology selection method.

Concerning the cost comparison of the alternative technologies, changing airline labour costs from differing aircraft layout, increase and decrease in flight crew demand and route and aircraft model specific cost, are excluded and assumed to remain same across all presented alternatives. Instead, the focus lays on the principle of Levelized Cost of Mobility (LCOM). Further limitations are the differing demands of the alternative technology towards airports, air traffic control and accurate operative procedures of airlines. Moreover, the recommended technologies are solely evaluated by their overall potential for implementation and cost benefits on different aircraft mission ranges and passenger capacities.
Structure

This thesis will be structured as displayed in the following:

![Input-Output diagram]

The inputs represent the flow of data and information necessary to create the content desired. The outputs are data and findings derived from the content. First, the relevance of the topic is introduced, and relevant background is presented. In the following, scientific literature is reviewed for principles of power plant technologies. Their GHG emission reduction potential and feasibility for replacing kerosene driven combustion engines are analysed. Thereafter, the methodology to be applied is presented. In the analysis, the technology alternatives are compared based on their performance in LCOM and Analytic Hierarchy Process (AHP). Last, the results are discussed, recommendations are provided, an overall conclusion is drawn, and further research activity is highlighted.
2. Power plant technologies

In the following, scientific literature is reviewed for alternatives to currently existing aircraft propulsion technology. Main alternatives are bio- and synthetic fuels, electric propulsion as well as hydrogen fuelled aviation. A summary of strengths and weaknesses of each propulsion concept is presented below.

Table 1: Results of literature review

<table>
<thead>
<tr>
<th>Technology</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
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<tbody>
<tr>
<td>Fossil jet fuel</td>
<td>Low fuel costs</td>
<td>High GHG emissions</td>
</tr>
<tr>
<td></td>
<td>High energy density</td>
<td>Volatile fuel costs</td>
</tr>
<tr>
<td></td>
<td>Global infrastructure</td>
<td>Dependence on finite resource</td>
</tr>
<tr>
<td>Bio- and synthetic fuels</td>
<td>Low to zero GHG emissions</td>
<td>Direct and indirect land use change</td>
</tr>
<tr>
<td></td>
<td>Unlimited resource availability</td>
<td>Maximum 50:50 blend certified</td>
</tr>
<tr>
<td></td>
<td>Available in near-term</td>
<td>Zero emissions only by synthetic fuels</td>
</tr>
<tr>
<td>Electric propulsion</td>
<td>Zero GHG emissions</td>
<td>Low energy density of batteries</td>
</tr>
<tr>
<td></td>
<td>High efficiency ratios</td>
<td>Electric devices &amp; aircraft in scale lacking</td>
</tr>
<tr>
<td></td>
<td>Independence from liquid fuels</td>
<td>Higher demand of renewable electricity</td>
</tr>
<tr>
<td>Hydrogen fuelled aviation</td>
<td>Near zero GHG emissions</td>
<td>New aircraft design &amp; production needed</td>
</tr>
<tr>
<td></td>
<td>Unlimited resource availability</td>
<td>High fuel cost</td>
</tr>
<tr>
<td></td>
<td>Low weight</td>
<td>Handling is challenging (-253°C)</td>
</tr>
</tbody>
</table>

2.1. Fossil jet fuel

In aviation today, two general types of engines are utilized: reciprocating piston engines and gas turbines (Olivier, 1991). Piston engines use the energy inside a combustion chamber through a piston and crank mechanism which drives a propeller (Rypdal et al., 2003, p. 94). In gas turbines, air is compressed and heated in a combustion chamber and predominantly used for propulsion. A minor part of the energy of the heated air is utilized for driving a turbine that moves the compressor. In turbojet engines the propulsion energy is solely derived from the expanding exhaust stream while in turbofan and turboprop engines the propulsion is created by energy from the turbine that drives a fan or propeller.

Generally, civil aircrafts are flying at subsonic speeds, only military jets and the aircraft Concorde exceed the speed of sound, thus fly at supersonic speed (Romano, et al., 1999, p.
54). Moreover, the aircraft mission and related fuel consumption and emission creation is divided in two parts: Landing and Take-off (LTO) for all activities below an altitude of 1 km and Cruise which is highly varying in length at altitudes between 8-12 km. A typical short-range flight applies the following engine standard operating modes:

<table>
<thead>
<tr>
<th>Operating mode</th>
<th>Thrust setting</th>
<th>Time in mode (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Take-off</td>
<td>100%</td>
<td>0.7</td>
</tr>
<tr>
<td>Climb</td>
<td>85%</td>
<td>2.2</td>
</tr>
<tr>
<td>Cruise</td>
<td>60%</td>
<td>30</td>
</tr>
<tr>
<td>Decent</td>
<td>30%</td>
<td>4</td>
</tr>
<tr>
<td>Taxi/idle</td>
<td>7%</td>
<td>26</td>
</tr>
</tbody>
</table>

It shall be noted that the given values are average figures, the actual values vary around these during the operating mode (Zaporozhets and Synylo, 2017, p. 3). However, it can be seen that high power demands are only required for short periods of time. Thus, engines must be designed for varying demands that remain unused during most parts of the mission. Besides cruise, taxiing and idle operating modes with low thrust settings and low power requirements are having the highest share. Despite the comparable low GHG emissions in these modes, alternatives for ground power supply are promising and discussed later.

The emissions of an aircraft are derived from fossil fuel that is burned in combustion engines. GHG emissions are products and side products of combustion. Overall, CO₂ and nitrogen oxides (NOₓ) are the GHGs with the highest Global Warming Potential. Nevertheless, methane, Unburned Hydrocarbons (UHC) and other by-product gases are likewise caused. How much fuel is burned and what kind of emissions are thereby emitted is reliant on fuel type, aircraft type and mission, type of combustion engine, climb speed, engine load and cruise altitude (Rypdal et al., 2003, p. 94).

To date, kerosene is used almost exclusively in aviation as the use of fossil fuels has been proven to be substantially beneficial. In 2016, 371 billion litres of jet fuel have been consumed by global aviation, representing 99% of the energy consumption of the sector (Yilmaz and Atmanli, 2017, p. 1383; Epstein and O’Flarity, 2019, p. 1). Kerosene is globally available at comparably low, but volatile cost and its easy handling made the development of a vast logistical infrastructure possible (Teichmann et al., 2012, p. 18118).
Compared to the electricity price, the price of kerosene is about the same, but clearly more volatile and strongly dependent on global economic trends. The dependence on relatively few extracting countries makes it challenging to react on price fluctuations. Overall, countries are more independent on electricity prices and uncertainty is reduced.

The main advantage of kerosene is its energy density and globally existing infrastructure. Moreover, many years of research and development have brought jet turbines to a technology maturity that is unbeaten. Newest engines achieve outstanding efficiencies in fuel consumption and noise. The accomplishments in any other alternative propulsion technology are in early stages. A simple comparison shows the substantial performance gap between jet fuel driven aircraft and alternative propulsion technology, hereby an electric aircraft. In 2012, the fastest electric aircraft flown flew at speeds of 0.27 Mach with a single passenger whereas the Airbus A350XWB-900 can carry 440 passengers at a maximum speed of 0.92 Mach (The flight of the century, 2017; Airbus, 2019).

Requirements of an aircraft propulsion system are complex and comprehensive. Premise is a wide range of operating speed, varying temperatures, little ambient pressure, high tolerance for vibration, safety, reliability and operating cost (Epstein and O’Flarity, 2019, p. 6). Thus, finding a suitable alternative is challenging. IATA predicts that a shift towards non fossil fuel based aviation would be unrealistic before 2035 (IATA, 2018a, p. 35). Nonetheless, the sector should be prepared for radical disruptions in its energy supply in the coming years.

### 2.1.1. GHG emissions

In 2011, 54% of global petroleum resources have been consumed by the transport sector and in 2020, this figure is expected to rise to 74% (Yilmaz and Atmanli, 2017, p. 1378). The global aviation sector is taking part of this rising fuel consumption and related GHG emission. Currently, ICAO sets standards for emission certification of aircraft engines. From
1kg of kerosene burnt the emissions shall not exceed 3.16kg of CO$_2$, 1.29kg of H$_2$O, 15g of NO$_X$, 1.2g of SO$_X$, 0.6g of CO, 0.01g of HC and 0.05g of particulates (ICAO, 2008). However, the actual emissions intensity of the portfolio of jet engines in operations differs from these maxima. De Jong et al. assess the emission intensity of conventional jet fuel at 87.5 g CO$_2$eq per MJ and 3.745kg CO$_2$eq per kg of fuel burnt (De Jong et al., 2017, p. 5).

Due to increasingly stringent emission reduction targets, aircraft engine manufacturers perform continuous research and development activity in order to reduce the GHG emission intensity of kerosene driven jet engines. Especially noise and local air quality related to NO$_X$ emissions close to airports are to be reduced significantly by the introduction of new technology, such as ultrahigh by-pass ratio engines. These are expected to be 15% more fuel efficient, 30dB quieter and despite their higher share of NO$_X$ per amount of fuel burnt, lower overall NO$_X$ emission due to proportionally higher fuel savings (Hughes, 2011; Kestner et al., 2011, p. 6). Nevertheless, the aviation market growth is expected to outpace these technology improvements.

### 2.1.2. Jet fuel taxation

To date, jet fuel is tax free in almost every country. Besides developing alternative propulsion technology, aircraft fuel taxation represents an important and effective instrument to create a market-based incentive to lower kerosene consumption. Consequently, the price of kerosene does not reflect its environmental costs. Low kerosene prices compared to taxed road and rail transport make customers choose cheaper modes of transports which are linked to higher emissions. First attempts to introduce taxation on jet fuel have been made by single countries such as Japan, India and the USA, moreover, proposals were made to introduce it within the European Union (Hooper, 1997, p. 117; González and Hosoda, 2016, p. 237; Cramer, 2019).

Despite these national efforts viable for domestic flights, no global attempt is yet made. Furthermore, Fukui and Miyoshi conclude that kerosene taxation has certainly contributed to GHG emission reduction, nonetheless, its impact on airline’s fuel strategies is only marginal (Fukui and Miyoshi, 2017, p. 249). Hence, establish global kerosene taxation will have undoubtedly positive effects on GHG emissions and creates funds to invest in measures to reduce impacts of climate change. Nonetheless, its extent is considered to insufficient to reach a zero-emission scenario by 2050. Thus, alternative technologies gain importance.
2.2. Biofuels and synthetic fuels

Aviation represents a transportation sector that is hardly to be electrified (Fasihi, 2016, p. 10). Hence, when considering alternatives to jet fuel, the introduction of biofuels and synthetic fuels is the most obvious choice as they are already certified as alternative aviation fuels. Historic milestones of biofuels and synthetic fuels can be found below.

Table 3: History of bio jet fuel

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>First flight of aircraft using 100% biofuel by GreenFlight International</td>
</tr>
<tr>
<td>2009</td>
<td>First commercial flight with 50:50 blend of synthetic jet fuel operated by Qatar</td>
</tr>
<tr>
<td>2010</td>
<td>US Navy successfully tested biofuel blend in F/A-18 Super Hornet</td>
</tr>
<tr>
<td>2010</td>
<td>First 100% synthetic jet fuel passenger flight</td>
</tr>
<tr>
<td>2011</td>
<td>American Society for Testing and Materials (ASTM) approves standard specification D7566 of using 50% of biofuels in commercial flights</td>
</tr>
<tr>
<td>2011</td>
<td>KLM conducted first commercial biofuel flight with 171 passengers</td>
</tr>
<tr>
<td>2016</td>
<td>3-year contract between KLM and SkyNRG to operate all flights between Los Angeles and Amsterdam with biofuel blend</td>
</tr>
</tbody>
</table>

Biofuels are defined as fuels made of biomass energy resources which is biological material based on any agriculture or animal feed combined with carbohydrates (Nigam and Singh, 2011, p. 53; Yilmaz and Atmanli, 2017, p. 1379). Biofuels are available in gaseous, solid and liquid state. The latter has the potential to replace liquid fossil fuels and can be derived from vegetable oils, such as rapeseed, sunflower, soybean or oil palms or lignocellulosic and wastes/residues such as forest residues from stump harvesting or straw (Yilmaz and Atmanli, 2017, p. 1380; O’Connell et al., 2019, p. 509).
There are two ways of usage of biomass as biofuel. Primary biofuels are directly used for generation electricity or thermal energy through burning without any chemical processing. Secondary biofuels are converted before their end use and improve the properties of primary biofuels (Yilmaz and Atmanli, 2017, p. 1380). Second and third generation biofuels are considered to be more sustainable, as they include different feedstocks that compete less with food production. Hereafter, the term biofuel is likewise understood for biofuels and synthetic fuels.

Similar to biofuels is synthetic paraffinic kerosene, which is based on branched hydrocarbons and commonly called synthetic fuel (Stepan et al., 2016, p. 30). It is produced by catalytic conversion of syngas (CO and H2) by Fischer-Tropsch (FT) synthesis (Hari, et al., 2015, p. 1237; Mawhood et al., 2016, p. 10). Historically, it is not derived from biomass as feedstock, but coal or natural gas. Nonetheless, there is small scale production of biomass based synthetic fuel, e.g. in Varkaus, Finland by Neste and Stora Enso. Moreover, a couple of demonstration flights have been performed with 50% blend of synthetic fuel. Significant further development of the production process is required in order to provide this fuel in large amounts at lower prices, especially concerning handling of biomass feedstocks and syngas cleaning (Brown and Brown, 2013, p. 6; Maniatis, et al., 2013, p. 17).

In order to analyse whether the application of biofuels in aviation receives enhanced attention in research, a quantitative literature review is conducted. The review of the key words biofuel in aviation, bio jet fuel, synthetic jet fuel, synthetic paraffinic kerosene,
aviation biofuel, aviation synthetic fuel, sustainable jet fuel, renewable jet fuel and alternative jet fuel yielded 41,017 results.

During the last ten years, the research articles published increased by 11% per year in average and tripled from 2008 to 2018 in total. Thus, a steeply growing activity in scientific publications in the area of bio jet fuel may enhance further GHG emission reduction achievements of bio- and synthetic fuel, cost reductions, simplified application for aviation and discoveries of new feedstock and processes.

To date, second generation biofuels including synthetic fuels are considered to be the choice of replacing fossil fuels as they provide high GHG emission savings and cause less concerns about Indirect Land Use Change (EC, 2015, p. 2). Some argue that as being produced from inedible feedstock, second generation biofuels would do not affect the food chain. In contrast to this, production from lignocellulosic and wastes/residues does lead to that especially straw and stumps are not enriching the soils when being left on the fields/woods after harvesting. Hence, second generation biofuels affect the fertility of soil and biodiversity which indeed has an influence on the food chain (Yilmaz and Atmanli, 2017, p. 1383).

To a significantly larger extent, first generation biofuels are causing competition for growing crops and food products besides indirect land use change (ILUC). Thus, usage of first generation biofuels has been limited, e.g. by the EU Directive 2015/1513. Biofuels produced in new installations shall emit at least 60% less GHGs than fossil fuels. This shall contribute

### 2.2.1. Conversion pathways and feedstocks

The production of biofuels from biomass consists of three consecutive steps: crop cultivation, feedstock processing into fuel and transportation towards the end-use (O’Connell et al., 2019, p. 508). A description of the process of converting feedstocks to biofuels can be found below.

![Biofuel and synthetic fuel conversion pathways](Mawhood et al., 2016, p. 3)

Different types of feedstocks are to be transformed by various processes into readily applicable biofuel. Most commonly used conversion pathways that are foreseen to become commercially available in the near future are hydroprocessed esters and fatty acids (HEFA), FT, pyrolysis, Hydrothermal liquefaction (HTL), alcohol to jet (ATJ) and direct sugars to hydrocarbons (DSHC) (De Jong et al., 2017, p. 6). Out of these, HEFA, FT, ATJ from butanol and DSHC are certified to be blended with kerosene by ASTM. Nonetheless, to date, HEFA is the only mature pathway that can be scaled up without large improvement requirements (EC, 2013, p. 16).
Feedstocks for biofuels can be sugarcane, corn, canola, soybean, cotton, lignocellulosic (poplar, straw, willow, corn stover and forestry residues) and vegetable oils (used cooking oil, coconut, palm, jatropha, camelina and algae) (Yilmaz and Atmanli, 2017, p. 1380; De Jong et al., 2017, p. 3). For primary biofuels main feedstocks are rapeseed in central and northern Europe and sunflower seed in southern Europe (O’Connell et al., 2019, p. 509). Globally, soy oil produced in the Americas and palm oil from South East Asia are important food-crop type feedstock. Second generation biofuels are based on lignocellulosic biomass and waste and residue based as well as all feedstocks applied for synthetic fuels.

A crucial effect of biofuel production are emissions from direct land use change (LUC) and ILUC. These may impact the GHG emission performance of biofuel conversion pathways significantly (Bailis and Baka, 2010, p. 8689; De Jong et al., 2017, p. 3). They are caused by above- and below-ground carbon stocks as a result of changing former land use to cultivate biomass for bioenergy purposes. Changing land use that is diverting existing feedstock cultivation to produce feedstock utilized for biofuel production may lead to land use changes elsewhere to restore required levels of food, feed and materials (De Jong et al., 2017, p. 3). Hence, indirect LUC emissions are caused which signify additional negative GHG emissions of biofuels. Nevertheless, they are excluded from the calculation of specific GHG emissions from biofuel by most of the studies as they are challenging to quantify combined with major uncertainties and circumstances such as soil type, previous land use and management practices are highly fluctuating (Wicke et al., 2012, p. 92). A solution could be utilizing feedstock such as algae since it does not affect land use for crop cultivation (Yilmaz and Atmanli, 2017, p. 1380).

### 2.2.2. Aviation specific requirements

Biofuels have been successfully used in road transport for decades. Nevertheless, not the same fuels can be used in aviation due to higher quality requirements. Aviation biofuels need to be certified by ASTM and Defence Standards Agency. Some criteria are high heat content, good burning characteristics, low explosion risk, low viscosity and good thermal stability (Maurice et al., 2001, p. 747). In order to efficiently use biofuels in the aviation sector, they shall derive from inedible feedstock that is not competing with crop and food production and does not signify ILUC. Moreover, alternative jet fuels shall use renewable resources, have reduced GHG emissions, be sustainable and burn cleanly, meet standards of chemical properties, safe to store, easy to transport and shall be compatible with conventional fuel in
terms of combustion technology and infrastructure (Hari, et al., 2015, p. 1237; Yilmaz and Atmanli, 2017, p. 1381). Principally, jet fuels require more demanding chemical properties, thus additional processes for improvement of fuel properties of specific ground transportation fuels would have to be necessary at a certain cost. Hence, e.g. biodiesel which lacks of sufficient fuel properties cannot be used for aviation in an economic manner (Daggett, et al., 2006, p. 5).

Important advantages when introducing biofuels are to decrease dependency on fossil fuels, reduce GHG emissions of global aviation, increase fuel efficiency and promote the development of rural areas through offering new job opportunities (Nigam and Singh, 2011, p. 55; Yilmaz and Atmanli, 2017, p. 1381). Biofuels are sustainable alternatives for fossil jet fuels which are hydrocarbon fuels that can be mixed with conventional jet fuels as they have the same chemical properties. Due to their similarities, they can be supplied through the same infrastructure than fossil fuels and used by all existing aircraft power plants. Furthermore, since ASTM passed the approval standard specification D7566 of using a 50% blend of biofuels in commercial flights in 2011, numerous airlines are involving increasingly in the use of biofuels (ASTM, 2011; ICAO, 2011, p. 6; Yilmaz and Atmanli, 2017, p. 1384). Moreover, with regard to the CORSIA scheme, biofuels may be accepted as one of its carbon offsetting measures (ICAO, 2016b, p. 2).

However, biofuel production has several drawbacks. The most crucial one is the feedstock resource limitations and related competition as agricultural product with land use for food and crop production (Koizumi, 2015, p. 837). Thus, with increasing use of biofuels as alternative to jet fuel the competition for finite resource of agriculturally usable land aggravates with the risk of increasing carbon intensive LUC. These drawbacks do not apply for synthetic fuels, thus further research to make this option more cost-competitive and scale up existing production facilities is highly recommended.

2.2.3. GHG emission reduction potential

When considering biofuel as alternative to jet fuel, the main aim is to reduce GHG emissions occurring from the combustion of fuel in order to accomplish the global warming reduction intentions of the Paris Agreement. Concerning biofuels, EU renewable energy directive and US renewable fuel standard established stringent emission reduction thresholds of 60% compared to fossil jet fuel of 87.5g CO₂ eq/MJ (De Jong et al., 2017, p. 9). According to the
life-cycle assessments conducted by De Jong and O’Connell, most second generation biofuel production pathways can comply with this target (De Jong et al., 2017, p. 9; O’Connell et al., 2019, p. 510). Specific life-cycle assessment of GHG emissions of different biofuel production pathways is shown in the following figure.

Figure 12: Life-cycle GHG emissions of biofuel pathways, adapted from (De Jong et al., 2017, p. 10)
Conversion pathways based on residues or lignocellulosic crops show constant low GHG emissions. Especially the FT process has the highest GHG emission reduction potential (86-104%) across all feedstock which is based on the self-sufficient process and electricity production from excess energy. Corn-based ATJ and sugarcane-based DSHC show high GHG emission which is mainly due to fossil energy demand during conversion for corn and low conversion efficiency and high hydrogen demand of the DSHC process. Nevertheless, the outcomes are highly dependent on applied comparison methodology and especially on allocation method of GHG emissions on co-products.

First generation biofuels derived from oil crops such as sunflower seed, rapeseed and oil palm show up to 50% GHG emission reduction potential, but are considerably higher emissions mainly due to fertilizer use, feedstock collection and emissions from crop cultivation especially when peat lands are used instead of mineral soils (De Jong et al., 2017, p. 9; O’Connell et al., 2019, p. 510). Palm plantations for example on 100% peat land including effects of direct LUC show GHG emissions of up to 642.1 g CO₂ eq/MJ which is significantly higher than the fossil fuel baseline. Thus, it is of great importance that the correct pathway for biofuel production is chosen and that this alternative for kerosene is not generalized as non-polluting. Residues and lignocellulosic crops are overall emitting lower levels of GHGs than food crops. However, biofuels produced from highly productive food crops transformed in efficient conversion pathways (e.g. sugarcane based ATJ) do also meet the most challenging GHG emission reduction thresholds.

Throughout all production pathways, hydrogen is an important contributor to general GHG emission. All conversion pathways of biofuels require hydrogen except FT, HTL and pyrolysis. It is crucial for the GHG emission balance of biofuels through which production method the deployed hydrogen is obtained. In both life-cycle analysis based GHG emission calculations by O’Connell and De Jong, hydrogen was assumed to be produced via steam methane reforming of natural gas as it reflects the largest part of current hydrogen production methods (De Jong et al., 2017, p. 6). Nevertheless, technological advancements and especially higher share of renewable electricity can make more sustainable hydrogen production technically and economically feasible. De Jong performed a sensitivity analysis on alternative hydrogen production methods, which were electrolysis using renewable
electricity from wind, solar PV and biogas from waste and gasification of switchgrass as biomass.

![Figure 13: Sensitivity analysis of hydrogen production method (De Jong et al., 2017, p. 12)](image)

From this analysis, it is observable that alternative hydrogen generation methods can clearly reduce GHG emissions of biofuels, especially for hydrogen-intensive pathways such as pyrolysis (-71%) and HTL (-48%). Hence, choosing a carbon extensive hydrogen production technology makes an important contribution to further reduce the emission intensity of biofuels. Moreover, hydrogen consumption reduction potential during biofuel production pathways should be considered, e.g. by careful choice of feedstock, catalyst and process.

When it comes to the geographical location of biofuel production, feedstocks used, and electricity generation methods vary significantly. In Brazil, sugarcane-based pathways are prevailing due to their favourable electricity mix with a higher share in renewable energy, e.g. from hydropower, that outweighs the higher electricity demand for conversion. In the US, a very carbon intensive electricity mix is provided, other production methods are chosen. As fuels can be transported easily at low emissions, countries equipped with a low carbon
intensive energy mix are more likely to be chosen for biofuel supply than other countries. This may even develop into a market-based measure for biofuel production.

In many literatures, the focus often lays upon reduced GHG emissions with less attention towards the aspect of energy efficiency. Nonetheless, as the sector projects dramatic growth rates, it becomes increasingly important how resources, in case of biofuels, feedstock, are used (O’Connell et al., 2019, p. 505). Thus, it is crucial to not only compare possible biofuels to be recommended according to their GHG emissions, but also energy balances. Moreover, the extent to which biofuels may contribute to the emission reduction ambitions of the aviation sector depends on the degree of market penetration and the fuels GHG emission reduction potential (De Jong et al., 2017, p. 2). To date, the former has been negligible due to high prices and limited production capacity. If biofuels can contribute to a more sustainable aviation sector is highly dependent on a lower GHG emission balance and adherence to sustainability constraints.

Lee et al. conducted research about closing the gap between aviation’s emitted GHGs and its reduction goals.

![Figure 14: Contribution potential of alternatives to limit global GHG emissions of aviation (Lee, et al., 2013, p. 17)](image_url)

They conclude that none of the most realistic efforts, such as business as usual scenarios including technology improvements, realistic biofuel penetration and extension of existing market based measures will close the CO₂ gap (Lee, et al., 2013, p. 22). Even by implementing a global market-based measure scheme based on emission savings from outside of the aviation sector which are offering the highest potential of GHG emission reductions cannot close the gap. Hence, other propulsion alternatives need to be discussed.
2.3. Electric propulsion

Considering the efforts towards lowering GHG emissions currently achieved in the automobile sector, electric and hybrid drive trains are the obvious technologies to be introduced. They offer the opportunity to not combust fuel and not emit any GHGs to the atmosphere and thus have the potential to significantly reduce the impacts of aviation on climate change in order to reach the ambitious targets set (Gnad et al., 2019, p. 1). However, in aviation, electric propulsion is facing significantly different requirements and challenges. Overall, it is anticipated that electric propulsion is equipped with the advantages of lower carbon emissions, less emitted noise, reduced operating cost and more flexible aircraft configurations (Epstein and O’Flarity, 2019, p. 1). Consequently, since the 1970’s, a large number of solely electrically powered aircraft in small scale became into service and more are recently under development.

Table 4: History of electric aircraft propulsion

<table>
<thead>
<tr>
<th>Year</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1883</td>
<td>1st electrically powered airship went airborne in France</td>
</tr>
<tr>
<td>1973</td>
<td>In Linz, Austria the first electric aircraft, a modified HB-3 power glider, took off, lasting 9 min &amp; reaching a height of 300m</td>
</tr>
<tr>
<td>1983</td>
<td>Unmanned Aerial Vehicles powered by solar PV &amp; fuel cells are utilized by NASA</td>
</tr>
<tr>
<td>2007</td>
<td>1st flight of serial produced electric two-seater Pipistel Taurus Electro</td>
</tr>
<tr>
<td>2016</td>
<td>Battery &amp; solar PV powered Solar Impulse 2 flies around the world in 16 stages</td>
</tr>
<tr>
<td>2035</td>
<td>Electric aircraft in the scale of a single aisle aircraft are expected to enter into service, e.g. Boeing SUGAR Volt, Bauhaus Luftfahrt Ce-Liner, Airbus VoltAir, Wright One</td>
</tr>
</tbody>
</table>

Despite a vast number of electric aircraft being under development, these models are prevailing very small aircraft (<6 seats) with short ranges (<350 km) and low cruise speeds (<0.3 Mach). Any all-electrically powered commercial aircraft in the size of current most common aircraft type, single aisle jets such as B737 and A320, are not existing yet, not to speak of twin aisle aircraft. Despite several design projects for single-aisle sized aircraft being in development and expected to enter into service in 2035, a MIT study of Gnad et al. prospects that all-electric aircraft with 180 passengers are unlikely to be feasible with current battery technology (Gnad et al., 2019, p. 26).
A quantitative literature review including the keywords aircraft electric propulsion, electric aircraft, all-electric aircraft, all-electric aviation, electric aviation, turboelectric aircraft, hybrid electric aircraft and propulsive electric power provided 39,746 results.

![Electric aircraft literature review](image)

**Figure 15: Quantitative literature review of electric aircraft as of 19.03.2019**

During the last ten years, the amount of research articles published increased by 12% per year in average and in total grew more than three times from 2008 to 2018. As result of the enhancing scientific activity in electric aviation, the amount of aircraft models under development increase in size. Several alternatives to kerosene driven single-aisle jets are examined. However, the gap of research in battery technology is required to be closed most urgently and advancements are key for feasibility of all-electric aircraft.

In general, an electric propulsion system includes the following key elements: energy storage, generator, rectifier, motor, inverter, bus, motor controller and fault current limiter (Felder, 2015, p. 4). The technology included in the system is depending on which principle is applied. Overall, electric propulsion can be clustered in three different principles according to their degree of electrification: hybrid electric, turboelectric and all-electric (Epstein and O’Flarity, 2019, p. 4).

### 2.3.1. Hybrid electric

In hybrid electric propulsion battery energy storage and engines are used in series, parallel or as a combination of both including a fuelled combustion engine.
A series hybrid propulsion consists of an electrical coupling, such as a generator and a battery which both supply power to the engine (Bradley and Droney, 2015, p. 178). In a parallel hybrid propulsion, a mechanical coupling is installed between the components that are supplying power, which are a combustion engine and a battery. In hybrid aircraft, electricity from grid may be used for shorter missions and the combustion engine may act as range extender. There are several small hybrid electric aircraft already on the market and under development. One of the largest electrical engines on-board can be found in a cooperative project of Airbus, Siemens and Rolls-Royce, the E-Fan X.

This aircraft study includes a serial-hybrid structure with integration of a 2MW generator, storage and motor (Airbus, 2017). Its first flight is expected to be in 2020.

Hybrid electric propulsion enables new aircraft configurations and may reduce the size of aircraft due to less complex propulsion systems. Moreover, it may bridge the not sufficient readiness of all-electric aircraft. Despite total mission energy required is rising by introducing hybrid electric aircraft, the amount of fuel burned during the flight and related GHG emissions are reduced when charging batteries on ground before take-off (Bradley and Droney, 2015, p. 11). However, the weight of the batteries plays a significant role. The degree of hybridization is an essential coefficient that needs to be considered precisely. Overall, the aircraft efficiency decreases steeply with rising degree of hybridization due to poor gravimetric energy density of current batteries making combustion engines more
efficient for all significant ranges (Pornet and Isikveren, 2015, p. 134). In case the additional weight of the batteries eliminates the fuel reduction and increase in overall efficiency of the propulsion system, the net improvements in GHG emission reduction is negative. Only by introducing advanced electric system technology and enhanced battery energy density by 500-600% a 5% fuel consumption reduction can be achieved for a single-aisle hybrid electric aircraft on a 1700 km flight in case the electricity is derived from renewable sources (Lents et al., 2016, p. 12).

In hybrid electric aircraft, overall GHG emissions are reduced. NO\textsubscript{X} emissions are reduced due to reduced peak power of the combustion engine and lower fuel burn. Moreover, lifecycle CO\textsubscript{2} emissions can be reduced in case the renewable electricity is applied (Bradley and Droney, 2015, p. 63). A study of the hybrid electric aircraft SUGAR Volt demonstrate reduced landing and take-off emissions at 89-93% below compared to requirements of CAEP/6 (Bradley and Droney, 2015, p. 56). During cruise, this model shows 74% emission reduction compared to a common kerosene combustion engine, e.g. CFM-56. One variant of the studied hybrid electric aircraft, the Core shutdown with a range of 1667 km, can be flown electrically without emissions during half of the cruise time. This advantage would be especially important when further developed for long range aircraft as significant emissions originate from cruise.

From a cost perspective, hybrid electric propulsion is expected to be double as expensive for airlines in capex and opex terms as kerosene driven combustion engines due to the fact that both systems would need to be acquired and maintained (Epstein and O’Flarity, 2019, p. 7). Nevertheless, as both systems are only required in a smaller scale respectively, it is hereby assumed that the capital cost would rise less than double. Additionally, operating cost rises as the battery must be replaced or maintained on a regular basis. Another major drawback of hybrid electric propulsion is that both the combustion engine technology and the electric systems elements need to be carried on the plane and thus weight reductions are challenging to accomplish. Nonetheless, without improvement in battery technology it is highly unlikely to fly purely electric. Hence, hybrid electric solutions may play a role for reducing GHG emissions to some extent. Scientific activity is key for further technology improvement and several industrial projects are dependent on it, such as intentions of Airbus to power its future single aisle aircraft by hybrid electric propulsion (Poulton, 2019).
2.3.2. Turboelectric

Besides hybrid electric propulsion, another electric propulsion principle is turboelectric propulsion.

![Turboelectric](image)

*Figure 18: Turboelectric aircraft propulsion (Jansen et al., 2017, p. 4)*

In this principle, the propulsion energy is stored as liquid fuel which drives a combustion engine that is propelling a generator that is driving one or more electric motors creating propulsive power. In most of the cases, there is no energy storage in form of batteries included, as there is too less opportunity for regenerative braking and thus no energy to be recaptured (Bradley and Droney, 2015). Turboelectric aircraft can furthermore be designed as partial-turboelectric using the combustion engine propulsion partly to directly drive propulsors and partly to drive electric generators powering electric engines. The largest design study for a turboelectric aircraft is the N3-X concept conducted by NASA and Boeing.

![N3-X](image)

*Figure 19: N3-X turboelectric concept design (Felder, et al., 2013, p. 6)*

This study is proposing a hybrid wing body configuration including distributed propulsion and superconducting electrical components. Its feasibility to implement remains uncertain due to lack of mature technology.

Overall, turboelectric propulsion is considered to be equipped with electric efficiencies of around 80-90%.
The component efficiencies of 98% displayed above are objectives set by NASA for an advanced 2.6MW electric drive system. National Academies of Sciences made more conservative assumptions of 95% electrical component efficiencies, reducing the electric efficiency to 80% (National Academies of Sciences Engineering and Medicine, 2016, p. 61). Compared to direct mechanic drive, which is driving the propulsor with an efficiency of 99.5%, turboelectric approaches are experiencing a 10-19.5% efficiency penalty. Consequently, the higher degree of electric system components of turboelectric propulsion is emitting more waste heat than conventional combustion engines. This is adding another 3% decrease in efficiency. Hence, the fuel burn and related GHG emissions need to exceed at least 13% in order to make turboelectric propulsion more attractive for reducing emissions of aviation than purely kerosene driven combustion engines.

Additionally, turboelectric propulsion system capex and opex cost compounds are comparable with those of conventional gas turbines (Epstein and O’Flarity, 2019, p. 7). Since both technologies are needed on a turboelectric aircraft, this propulsion technology is double as costly as conventional one. Assuming that the engines accounts for roughly 20% of capex costs of airlines and turboelectric engines would higher the costs for airlines in this range, there would need to be fuel cost savings achieved not less than this amount. Equal cost enhancements for opex are expected, letting the maintenance costs double for airlines for a turboelectric system. Nonetheless, the actual prices are challenging to predict as required large devices are not existing yet. However, it is hereby assumed that for a turboelectric propulsion system the cost penalty would be less than +20% for capex and opex respectively, as both systems are required only in a smaller scale. The overall cost for airlines for hybrid electric and turboelectric propulsion is expected to be higher than kerosene driven combustion engines, especially due to the immature state of technology and redundant technology to be carried in-flight.
To be concluded, hybrid- and turbo-electric aircraft offer the potential to lower fuel consumption and therefore decrease GHG emissions of global aviation. Nonetheless, with introduction of neither of these technologies a zero-emission target can be reached.

2.3.3. All-electric

Only the principle of all-electric aviation powered by electricity from renewable sources offers the potential to reach a zero-emission scenario.

![All Electric Image](image1)

*Figure 21: All-electric aircraft propulsion (Felder, 2015, p. 4)*

All-electric propulsion is a battery powered propulsion in which all the energy consumed during the flight is stored electrochemically (Gnadt et al., 2019, p. 2). A comprehensive survey of all-electric aircraft was conducted by Gnadt et al. and can be found in Annex I. Again, it can be seen that most of the electric aircraft on the market are vertical take-off and landing vehicles and light aircraft. Narrow body aircraft are existing only in the conceptual design or development phase, let alone the non-existence of wide body aircraft which are causing the majority of GHG emissions of aviation.

In contrast to aircraft combustion engines, electric propulsion systems are not limited to thermodynamic efficiency limits and thus achieve a higher on-board energy conversion efficiency (Hepperle, 2012, p. 8). An overview about efficiencies of the different propulsion technologies can be found below.

![Efficiency Image](image2)

*Figure 22: Kerosene based turbofan propulsion efficiency, adapted from (Hepperle, 2012, p. 9)*
Kerosene based turbofan propulsion reaches overall efficiencies of 33%, mainly due to losses from the thermodynamic cycle. The efficiency of liquid hydrogen-based aviation follows similar values but varies dependent on the aircraft range.

Hydrogen fuel cells achieve a distinctly higher efficiency of 44%. Yet, the fuel cell accounts for a large part of the losses.

All-electric aircraft are benefitting from a higher overall efficiency than combustion engines and turboelectric propulsion (Brelje and Martins, 2019, p. 4). Overall on-board energy conversion is 2.2 times higher in electric propulsion systems than kerosene driven combustion engines and 1.65 times higher in hydrogen fuel cell propulsion systems. On the other hand, electric aircraft would require additional 8-10% of electricity for de-icing and cabin pressurization which is in conventional aircraft gained from bleed air of the turbine.

When discussing all-electric airplanes as alternative to kerosene driven combustion engines, the major performance limit of this propulsion technology is the necessity for utilized batteries to reach comparable specific energy and specific power. Specific energy is energy per unit mass of energy storage and specific power is power of a component per unit mass.
Research in battery technology receives significant funding and has a very high priority in many industries in order to achieve decarbonization across sectors. Nonetheless, batteries have much lower specific energy than liquid fuels. The specific energy of jet fuel is 11900 Wh/kg whereas it is indicated to vary around 200-600 Wh/kg for lithium-ion batteries (Brelje and Martins, 2019, p. 3; Epstein and O’Flarity, 2019, p. 3; Gnaadt et al., 2019, p. 7). Other battery concepts, such as lithium-sulfur batteries offer significantly higher energy densities, but these batteries are not applicable for aviation due to their low cycle life (Gnaadt et al., 2019, p. 7). For future time horizons, advanced concepts expect specific energy of up to 1000 Wh/kg in batteries to become realizable (Rheaume and Lents, 2016; Jansen et al., 2017, p. 10). However, the design of battery energy storage with current specific energy features would be 20-50 times heavier for providing the same energy than kerosene.

This higher weight has a significant impact on electric aircrafts range, as range is directly proportional to specific energy (Brelje and Martins, 2019, p. 3). When simply transforming energy storage in form of kerosene to batteries, the take-off gross weight of electric aircraft would increase extremely which further raises total energy consumption. Moreover, the weight of electric aircraft is discriminated compared to combustion engine driven aircraft by the Breguet range equation effect which describes the decrease of mass when fuel is burned. Thereafter, an aircraft with a fixed mass, such as an electric aircraft, needs higher total energy than a fuelled aircraft whose mass decreases over the mission. Despite this effect is negligible for short range aircraft, a long range electric aircraft with 6500 km range would require 17% more total energy (Jansen et al., 2017).

Besides specific energy, electric aircraft face the challenge of varying power requirements during the flight. The power requirements during the flight are highest during take-off, climb
and reverse, lowest during cruise and approach and vary significantly which higher the difficulties in battery design.

![Graph showing specific power required during different flight phases](image)

*Figure 25: Specific power required during different flight phases (Epstein and O’Flarity, 2019, p. 2)*

Thus, electric drives have to be scaled for the maximum power required and as a consequence they are oversized for regular cruise conditions which signifies a weight penalty. Nevertheless, aircraft are not optimized for electric propulsion and new design of propulsion systems could overcome this penalty. Among others, this can be achieved by short-term overpowering the system during take-off, exploiting excess power capability during climb or simply flying at a slower cruise speed which would reduce cruise altitude and hence climb power requirements (Epstein and O’Flarity, 2019, p. 3). When decreasing the speed from Mach 0.82 to Mach 0.7, 15% of total energy can be saved (Epstein and O’Flarity, 2019, p. 4). Hence, the electric aircraft of the future would possibly fly at minor speed. Moreover, take-off power requirements could be reduced by allowing longer runways, reducing wing load or improving take-off high-lift systems. Such changes in airline routines towards improving the competitiveness of electric aircraft propulsion might contribute a considerable impact on lowering GHG emission of aviation and it is highly recommended to perform further research on these topics.

On the other hand, specific energy needed curing two typical flight profiles depend mostly on the duration of the cruise which makes it proportional to aircraft range.
Figure 26: Specific energy required during two flight profiles (Epstein and O’Flarity, 2019, p. 3)

From these two typical aircraft mission energy consumptions it becomes visible that the total energy consumption is mainly diverting by the length of the cruise. The typical long-range profile applied on twin-aisle aircraft has an energy consumption of 30 kWh/km and the typical short-range profile applied on single-aisle aircraft consumes 38.7 kWh/km. Hence, long range aircraft are consuming slightly less energy per km due to proportional savings of high energy consumption during take-off and climb. Nonetheless, the significantly higher total energy consumption of 170,000 kWh of a twin-aisle aircraft would require battery energy densities of ca. 7000 Wh/kg and a power-to-weight ratio of 6 kW/kg or energy densities of 6000 Wh/kg and a power-to-weight ratio of 12 kW/kg (Epstein and O’Flarity, 2019, p. 4). These necessary performance parameters can by far not be covered by recently available electric propulsion technology. Therefore, all-electric aircraft are yet only possible to be introduced on short ranges.

One critical aspect of electric propulsion is that required electric devices with outstanding specific power capabilities that are not available yet (Zhang et al., 2018, p. 777). As consequence, the power to weight ratio of electrical systems is too poor for merely scaling up existing machines. Therefore, only if specific energy of batteries rises significantly and the weight of the electric drive systems decreases by a factor of four, it would be possible to design and manufacture an aircraft comparable to current single-aisle models. However, this aircraft could not yet reach all of the performance requirements of recent kerosene driven aircraft.
Furthermore, the batteries required to power an aircraft may be necessarily installed partly in cargo space and thus reduce the payload capacity of the aircraft. Additionally, the most limiting design parameter is range. There are different studies proposing varying predictions of possible electric aircraft properties. First, Epstein and O’Flarity conclude that in case a electric propulsion system with 12 kW/kg power-to-weight ratio and batteries with 1500 kWh/kg gravimetric energy density could be realized, a single-aisle type of aircraft would have a range of 300 km (Epstein and O’Flarity, 2019, p. 4). Second, Gnadt et al. come to the outcome that the best possible electric aircraft design shows performances of 800 Wh/kg battery density, 109.5 t weight and a range of 926 km (Gnad et al., 2019, p. 15).

The proposed design includes distributed propulsion of four propellers due to trade-offs between fan efficiencies, drag, landing gear length and weight and electric device weight. Third, another comparable study of Bauhaus Luftfahrt proposes an all-electric aircraft design with 2000 Wh/kg battery energy density reaching a cruise speed of 0.75 Mach and a range of 1667 km at a weight of 109.3 t (Hornung et al., 2013, p. 9). Overall, the projected electric aircraft ranges are highly varying and clearly lower than the comparative model, the A320.
The high variance of proposed ranges due to changing assumptions of battery specific energy performances leaves considerable uncertainty about future ranges and therefore the qualification of electric aircraft to replace kerosene fuelled aircraft. Despite one of the proposed designs may reach a range that is sufficient for 80% of all flown ranges by single-aisle aircraft and thus offers the benefit of reducing 28.8% of kerosene consumed, it is unlikely that this aircraft will be commercially available before 2035. Moreover, airlines are expected to only acquire aircraft with higher ranges due to their flexible utilization on differing missions. In case the more pessimistic approach of Epstein and O’Flarity becomes reality, 99% of the GHG emission of aviation are caused on flights with longer ranges than the predicted 300 km range. Hence, an electric single-aisle aircraft at current and predicted future technology level is unlikely to contribute significantly to the zero-emission target.

Moreover, electrifying aviation would increase the global electricity demand by 26% (Epstein and O’Flarity, 2019, p. 10). As there are considerable challenges to transform global energy consumption to renewable electricity, this rise in primary energy demand would even complicate the bottleneck. Despite electric technology is not ready to replace current most used aircraft types, single-aisle and twin-aisle aircraft, it still delivers several advantages over gas turbines. First, a new configuration of engine design is possible. Second, electric engines maintain propulsion performances at higher altitudes where combustion engines are not as efficient (Gaj, 2018). Thus, less power is required to achieve comparable speeds.

Furthermore, there are possibilities to increase the technologically readiness of electric aircraft propulsion such as the principle of distributed propulsion. It uses multiple smaller propulsors, which is on the one hand more complex and challenging to integrate into the airframe and increases the size of the propulsion system components (Gohardani et al. 2011, p. 388; Epstein and O’Flarity, 2019, p. 6). On the other hand, it offers the benefits of shorter take-off and landing, lighter and quieter engines, enhanced redundancy, increased efficiency and reduced capex due to higher manufacturing volumes and simplified maintenance due to design as line-replaceable units (Gohardani, et al., 2011, p. 370; Gnadt et al., 2019, p. 2). Moreover, a great part of aircraft electrical equipment is designed to be exchanged on the flight line which would save 8-16h that is required for an combustion engine change (Epstein and O’Flarity, 2019, p. 7). Distributed propulsion plays a significant role to enhance the competitiveness of hybrid electric propulsion, since with this concepts, synergies between airframe and propulsion systems can be enhanced (Pornet and Isikveren, 2015, p. 134).
Another aspect that is potentially enhancing weight and efficiency performance of electric propulsion is the principle of superconducting materials.

These materials demonstrate close to zero resistance at very low, cryogenic operating temperatures by almost avoiding Joule heating (Brelje and Martins, 2019, p. 12). Applying superconducting approaches in aircrafts would allow compact and lightweight electrical engines that exhibit very high power density and would lead to decreasing weight and GHG emissions (Masson and Luongo, 2005, p. 2229). In a proposed superconducting design of a Cessna 172 engine weight reductions of 56.25% compared to a conventional engine can be achieved. Nonetheless, there is high doubt in related literature, that a reliable usage of superconducting technology in aviation can be reached before 2040 (Zhang et al., 2018, p. 771; Brelje and Martins, 2019, p. 8).

Another aspect of reducing the total energy consumed could be regenerating power during speed decrease and descent, comparable to regenerative braking in hybrid and electric cars. However, this principle is offering only little efficiency gains as aircraft are not explicitly perform braking (Brelje and Martins, 2019, p. 2). Instead, excess energy occurring when ram drag slightly exceeds engine thrust can be used as range extension (Epstein and O’Flarity, 2019, p. 5). Nonetheless, less than 0.5% of the total mission energy is available for capture. Thus, for aircraft, energy regeneration plays an insignificant role in electric engine design.

Besides using electric power for propulsion purposes, aircraft have been more and more electrified in recent years, replacing hydraulic, mechanical and pneumatic systems with their electric equivalents (Gnadt et al., 2019, p. 3). This is summarized under the more-electric aircraft principle which is applied in new aircraft models, such as Boeing 787 and Airbus A350. The main purpose is to decrease weight, limit total power consumption and reduce Opex by decreased maintenance needs (Sarlioglu and Morris, 2015, p. 56).

In contrast to the concept of storing electricity and charging electric-aircraft’s batteries on ground, also solar PV aircraft are existing. However, such concepts such as the Solar Impulse
are far from being feasible for commercial passenger transport. Nonetheless, several activities are started towards supporting the shift towards electric aviation. For example, the airport London Heathrow will grant one year of free landing fees to the first electric passenger aircraft that is landing there, a price worth of 1 million pounds. Moreover, Norway is supporting airport infrastructure that makes electric flight attractive to use. In case electric aircraft enter into service, the airport energy supply is required to change. Today, large airports provide only <1% of their energy in form of electricity which is mainly consumed by buildings (PANYNJ, 2014, p. 15). More than 99% is provided by jet fuel. In order to provide the rising demand of electricity once regional and short-range flights are conducted by electric aircraft, renewable energy power plants of ca. 3MW size need to be installed.

Overall, electric aircraft show the potential to lower GHG emissions of aviation compared to conventionally kerosene powered aircraft in case the electrical grid has a higher renewable energy share than projected today. In case this transformation towards clean energy sources is not accomplished, the projected GHG emissions in 2040 of a grid-powered electric aircraft from power plant to propulsor of 516g/kWh would surpass current best combustion engines GHG emissions of 465g/kWh by 11% (IEA, 2017, p. 650; Epstein and O’Flarity, 2019, p. 9). Hence, it is only probable that electric aircraft significantly reduce GHG emissions of aviation when renewable electricity is available at airports.

2.4. Hydrogen fuelled aviation

An energy transition of the aviation sector is highly likely to lead to reaching climate targets. Hydrogen with its superior properties and features is discussed as adequate energy carrier to accomplish this transition (Sartbaeva et al., 2008, p. 80). The gas can be used as an alternative to kerosene either being burnt equally as conventional fuels in a combustion engine or as chemically reaction with oxygen in a fuel cell for electricity production. Already roughly 70 years ago, first applications of hydrogen as aviation fuel have been tested. Moreover, it is used as propulsion in most of space shuttles. Nevertheless, until today, the maximum capacity of a purely hydrogen fuelled aircraft is four passengers.
2.4.1. Production pathways

In the course of its production, hydrogen needs to be extracted from its combination with other elements, mostly hydrocarbon such as gasoline, natural gas, methanol or propane. Despite it is naturally not available for direct use, hydrogen can be produced from many different sources utilizing a variety of methods which enable a production in any country of the world (Mazloomi and Gomes, 2012, p. 3025). Its sources include feedstocks such as fossil resources, that is mainly chemically steam reformed natural gas or coal, or water and biomass, that is transformed via electrolysis using renewable energy resources as input power (IEA, 2006, p. 5). Alike, some algae and bacteria conducting photosynthesis produce hydrogen (Momirlan and Veziroglu, 2005, p. 796). An overview of the numerous hydrogen extraction options can be found below.

### Table 5: History of hydrogen fuelled aviation

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1957</td>
<td>1st successful test of the LH$_2$ use in the modified bomber aircraft B57 conducted by U.S. military</td>
</tr>
<tr>
<td>1988</td>
<td>1st flight of USSR’s Tupolev TY155 aircraft with one adapted Kuznetsov engine using LH$_2$ and natural gas</td>
</tr>
<tr>
<td>2003</td>
<td>Within the scope of the 5th European Commission Framework Program thorough studies concerning the transition from conventional to LH$_2$ fuel are undertaken</td>
</tr>
<tr>
<td>2016</td>
<td>1st flight of electrical 4-passenger aircraft HY4 powered by hydrogen fuel cell which was developed with the support of German Aerospace Centre “DLR”</td>
</tr>
</tbody>
</table>

Hydrogen is the most elementary and abundant chemical of this planet (Momirlan and Veziroglu, 2005, p. 795). Unlike fossil fuels it is never expected to be fully depleted, but it is expected to be available on the planet indefinitely (Quaschning, 2010, p. 10). Despite its simplicity it is not occurring as a single gas on the planet, it naturally only exists in combination with other elements.
Once extracted, hydrogen has a high energy content. Its specific energy of 120MJ/kg is 2.8 times higher than kerosene’s (42.8MJ/kg) (EEC, 2005, p. 7). This property decreases the fuel capacity required to cover the same flight range to nearly one third. Nevertheless, hydrogen is the lightest of all gases and thus voluminous. Especially in gaseous form it has a significant lower gravimetric energy density than kerosene. As consequence, its handling and application in gaseous form is not optimal. Hydrogen is liquified at temperatures below -253°C. Therefore, liquid hydrogen fuelled aircraft are often referred to as cryogenic planes or cryoplanes. Even after liquification, hydrogen possesses an energy density of only 8,697.24MJ/m³ which is 4.13 times lower than the energy density of kerosene (35,952MJ/m³) (Seeckt and Scholz, 2009, p. 3). Hence, this fuel requires significantly larger fuel tanks than kerosene and aircraft design will clearly need to change in order to accommodate this lighter, but more voluminous alternative fuel.

Research activity in this area is undergoing a significant increase. A quantitative literature review of the keywords hydrogen fuelled aviation, cryogenic aircraft, liquid hydrogen fuelled aircraft and cryoplane yielded 10,683 results.
During the precedent ten years, the research articles published increased by 13% per year in average and in total grew nearly three times from 2008 to 2018. Increasing research activity makes it more likely to reach further technology, cost and risk improvements. Nonetheless, research activity in electric aviation and biofuels for aviation is three to four times higher than in hydrogen fuelled aviation. However, in all categories, a greater than 10% annual growth of research activity can be recognized, making the amount of research articles triple every ten years. The probability for scientific discoveries in the field of alternative aircraft propulsion increases driven by a rising attention towards lowering overall GHG emissions.

### 2.4.2. Liquid hydrogen fuelled propulsion

As liquid hydrogen requires significantly larger fuel tanks, alternative aircraft designs need to be considered. Best insulation capabilities are reached by cylindrical tanks (Van Zon, 2018, p. 4). Weight simulations have shown that wing tanks as used in conventional aircraft would be too heavy for liquid hydrogen design. Moreover, the tank configuration varies depending on the aircraft range. A European Commission project coordinated by Airbus demonstrated three different possible design of hydrogen tank systems depending on aircraft range.
For small regional aircraft or business jets, tanks can be placed after the passenger cabin in the rear section of the aircraft.

For larger regional aircraft with less than 100 seats and medium range aircraft, it is optimal to place the tanks behind the cabin and additionally on top of the fuselage.

For long range and very long-range aircraft the tanks are also proposed to be placed behind the cabin and in addition in front, between the cabin and the cockpit. Passengers would walk past this front tank in a walkway alongside the tank (see arrow).

The modified aircraft configuration has the effect of a larger wetter surface which leads to an increase in energy consumption of 9% to 14% (EC, 2003, p. 3; Svensson, 2005, p. 143). However, the lower weight of LH₂ will compensate the aircraft empty weight increases for
installation of well-insulated fuel tanks. Hence, cryogenic aircraft will have a lower take-off weight of up to 15% which leads to the implementation of smaller engines and thus they will be clearly less noisy than kerosene fuelled aircraft (Brewer, 1991; EC, 2003, p. 17).

The resulting energy efficiency improvements are depending on the aircraft’s range. The take-off weight of long range liquid hydrogen fuelled aircraft is reduced by 30% which makes this propulsion alternative especially beneficial on long range flights (Verstraete, 2013, p. 14829; Baharozu, et al., 2017, p. 1369). On the one hand, this leads to energy efficiency improvements of long-range flights of up to 12%. On the other hand, short- and medium-range aircraft are up to 18% less energy efficient as the reduced fuel weight cannot compensate the increased weight and drag of the hydrogen tanks. Energy efficiency parity is projected to be reached at a range from 9000 km to 13000 km (Verstraete, 2015, p. 7393).

Furthermore, hydrogen based engines are expected to have simpler starting and ignition equipment, slightly lower turbine entry temperature and thus lower maintenance cost and longer lifetime (Brewer, 1991; Corchero and Montañés, 2005, p. 42; Mazloomi and Gomes, 2012, p. 3026). Moreover, the thermal energy radiation created by the combustion is up to 40°K lower for hydrogen than for kerosene, thus engine durability and cooling requirements are decreased (Corchero and Montañés, 2005, p. 42; Svensson, 2005, p. 143) The chemical properties of hydrogen are also causing a higher heat absorbing capacity, thus, the fuel can be more efficiently used for cooling the aircraft’s systems (EEC, 2005, p. 8).

The new aircraft design which is needed for hydrogen aircraft requires completely new production infrastructure and manufacturing processes. High investments would have to be made by the aircraft manufacturers and new maintenance procedures would need to be established. Moreover, the supply infrastructure for liquid hydrogen is not existing in a significantly large scale (Peters and Samsun, 2013, p. 47). These factors are clearly limiting the readiness and feasibility of this technology. On the other hand, sufficient investment sums could be sourced by a global jet fuel tax or ETS revenues. In an overall analysis they could cost less than opposing the negative effects of climate change caused by GHG emissions of aviation.

A crucial aspect to be particularly considered in aviation is safety. The gas is invisible and very flammable, but nontoxic (Verhelst and Wallner, 2009, p. 63). Hydrogen was initially applied as lifting gas in airships which were pioneers of civil aviation 19th and in the
beginning of the 20th century. Since this application had severe accidents as consequence, such as the disaster of the Hindenburg airship, the public image of utilizing hydrogen in aviation has suffered. Yet, the application of hydrogen for civil aviation has changed from lifting gas to compressed gas used in fuel cells or liquified as combustion fuel which changes the safety aspect fundamentally. Moreover, it is widely used in space missions without any incident (EEC, 2005, p. 7). Yet, in civil aviation more passengers are affected, thus its safety premises need to be revised. Solutions that guarantee safety on ground need to be found, such as application of non-combustion ground support vehicle (Svensson, 2005, p. 146). It is congruently approved that hydrogen fuelled aircraft will be at least as safe as kerosene fuelled aircraft (EC, 2003, p. 4; Verhelst and Wallner, 2009, p. 63). Safety regulations for the supply infrastructure of the gas would need to be reviewed, but as there is significant experience with its handling, hydrogen usage is considered as safe (Mazloomi and Gomes, 2012, p. 3027).

2.4.3. Fuel cell powered aircraft

A hydrogen fuel cell is an electro-chemical device in which hydrogen reacts with oxygen and produces electricity (Sartbaeva et al., 2008, p. 83). Due to the absence of combustion water vapour will be the only emitted GHG.

![Fuel cell model](Winter and Brodd, 2004, p. 4246)

Hydrogen and oxygen are fed into the anode and cathode of the fuel cell and driven by electrolytes as catalysts, a redox reaction occurs at the electrodes (Winter and Brodd, 2004, p. 4245). The electrolytes which can be acid, base, salt or solid ceramic or polymer, enables the ions to move between the electrodes when excess electrons reach through an external circuit and provide electrical current (Sartbaeva et al., 2008, p. 83). Throughout the process, fuel cells convert fuel into electricity with a significant higher efficiency as combustion engines (55% vs. 25%), because they are not subject to Carnot limitations (Von Helmolt and
Eberle, 2007, p. 836; Sartbaeva et al., 2008, p. 83; Peters and Samsun, 2013, p. 46). The produced electricity is used in electric engines that are generating thrust which is the main difference between liquid hydrogen fuelled engines.

When taking into account the continuous fuel supply during a long-term operation, the gravimetric energy density of hydrogen is higher compared to battery materials applied in electrical engines (Winter and Brodd, 2004, p. 4264). This makes fuel cells competitive to replace batteries for covering the increasing electrification of airplanes due to secure energy supply independent of the main power plant (Peters and Samsun, 2013, p. 46). A disadvantage of fuel cells is their high cost and their limited durability due to the abrasion of their membranes (Sartbaeva et al., 2008, p. 83). On the other hand, fuel cells include a lower amount of rotating parts and therefore decrease maintenance cost (Peters and Samsun, 2013, p. 47). Moreover, they are advantageous in satisfying low power, high endurance demands and thus the feasibility of propulsion for small unmanned vehicles has been proven and applied (Bradley et al., 2007, p. 800). Nevertheless, the replacement of a jet engine by a fuel cell as main propulsive power generator is considered to be unlikely due to their lower power density (Pratt et al., 2013, p. 792). Operating temperature limitation and low ranges allow only small aircraft to fly up to 1287 km on hydrogen fuel cells (EEC, 2005, p. 11).

Instead, multiple literature discusses the application of the hydrogen fuel cell as auxiliary power unit (APU) (Peters and Samsun, 2013, p. 62). To date, the APU acts as ground power supply or in in-flight emergency situations (Dollmayer et al., 2006, p. 687). Especially for long-range flight it remains unused during a large part of the mission. A fuel cell can power the aircraft’s electric systems independent from the main engines during flight including creating necessary heat and fresh water (EC, 2003, p. 21). Therefore, water storages can be reduced significantly (Dollmayer et al., 2006, p. 687). Moreover, the emission from taxiing are due to the close vicinity of large cities important to reduce. According to Zurich airport, per taxi-out operation GHG emissions of 707.2kg CO₂, 0.91 kg NOx, 0.92 HC and 8.87 kg of CO can be saved when applying a hydrogen fuel cell powered APU (Fleuti and Maraini, 2017, p. 16). This helps reaching airports targets of zero emissions from operation. 2020 is considered as possible starting date for introduction of hydrogen based APUs (IRENA, 2018, p. 34). Finally, it is recommendable to introduce fuel cells as APUs to facilitate research and development of handling hydrogen on-board of liquid hydrogen aircraft.
2.4.4. GHG emission reduction potential

Primarily, using hydrogen for propulsion offers crucial environmental benefits. In the following the exact GHG emissions caused by the combustion of related masses of hydrogen (0.36kg) vs. kerosene (1kg) with the same energy content of 11.89kWh are compared.

![Diagram of GHG emissions comparison](image)

**Figure 36: GHG emissions of hydrogen vs. kerosene**

It can be seen that the particular subsequent emissions are clearly lower in hydrogen aircraft (Brewer, 1991; EC, 2003, p. 59; EEC, 2005, p. 9; Nojoumi et al., 2009, p. 1365).

Thus, applying hydrogen powered aircraft will fulfil the IPCC goal of zero emission of GHGs. Only water vapour and a minor amount of NO\textsubscript{X} due to reactions with nitrogen from the air at high combustion temperatures are emitted (EEC, 2005, p. 5). In high altitudes,
starting from around 9 km for hydrogen and 10 km for kerosene H₂O emissions condense and form thin cloud trails, also called contrails.

Despite water vapour is a GHG when forming contrails, its effects on global warming, e.g. radiative forcing, is less significant than those of CO₂ and NOₓ at lower cruise altitudes (Nojoumi, et al., 2009, p. 1366). However, the higher emissions of water vapour and related contrails remain an uncertainty. The emitted water vapour is 4-5 times higher, followed by a larger coverage of contrails which has a significant global warming potential. Nonetheless, the contrails of cryoplanes are formed by 1-2 times fewer ice crystals which are 4-6 times larger than the ones by kerosene driven combustion engines and thus have a lower optical depth (Ström and Gierens, 2002, p. 1). Hence, the global mean radiative forcing of contrails of a fleet of cryoplanes despite regional variations would be 30% lower in 2050 than the extent of radiative forcing of conventional contrails as can be seen below (EC, 2003, p. 4; Marquart et al., 2005, p. 580).

The replacement of kerosene fuelled aircraft by LH₂ fuelled aircraft offers the opportunity to mitigate, stabilize and decrease the cumulative GHG emissions except water vapour in
the medium to distant future despite constant growth of global air travel (Janič, 2014, p. 228). The impact of cryoplanes on global warming are shown in the following.

![Figure 39: Global mean surface temperature change for kerosene vs hydrogen fuelled aviation (Ponater et al., 2006, p. 6942)](image)

After their entry into service, a significant reduction in global mean surface temperature increase can be observes compared to kerosene-based aviation. With cryoplanes, a neutral or even negative mean surface temperature change is predicted in the long run. Nevertheless, the positive effect for climate change can only be achieved by utilizing renewable energy resources for LH$_2$ production.

Besides the high GHG emission reduction potential of hydrogen fuelled aviation, there are other advantages, such as lower engine maintenance cost and independency of global feedstock supply. In contrast to fossil fuels, hydrogen as an aviation fuel ensures national independence of fuel supply since it can be produced worldwide (Janič, 2014, p. 229). After having developed suitable new aircraft production and fuel supply infrastructures, hydrogen fuelled aviation is a long-term alternative for kerosene as it emits only water vapour and minuscule amounts of NOx and offers unlimited resource availability compared to finite crude oil supply.
3. Methodology

The research methodology applied in this thesis is an explanatory collection and descriptive analysis of peer-reviewed data. A critical review of developed hypothesis is conducted followed by a comprehensive response. This is formulated as deductive approach, as in this thesis a conceptual framework was derived from the literature which was then tested using data and analysis frameworks. Moreover, basic research about technology functionality and comparison requirements is performed. The hypothesis and research questions are developed and adjusted in a dialogue. Moreover, brainstorming of keywords for literature review and qualitative and quantitative decision criteria was carried out in a single approach as well as in feedback reviews. Within the quantitative data analysis of cost data, available data is compiled before being analysed.

Within the deductive research approach the theoretical propositions are tested against confirmation by employment of a specific research strategy (Saunders, et al., 2009, p. 590). In this study, a mixed method approach is chosen as it is offering to decide upon the specific alternative from different aspects and viewpoints. Moreover, it helps in interpreting the right choice and delivers complimentary information. Furthermore, it facilitates to take an encompassing sustainable choice. On the one hand, quantitative cost data is collected, analysed and compared by calculating specific LCOM of the alternatives. On the other hand, there are qualitative decision criteria and related sub-criteria in the frame of AHP established. Thereby, quantitative and qualitative data analysis is performed one after another which indicates a sequential explanatory research design. The qualitative results are used to further explain the quantitative findings.

The time horizon analysed is the current time horizon. It was decided to not perform longitudinal research, but cross-sectional research of the performance of alternative propulsion technology against specific criteria as a snapshot. Besides that, certain future recommendations are given based on analysis of basic qualitative secondary data.

Furthermore, the literature utilized was derived from applied documentary and multiple sources. Documentary sources include scientific journal publications, textbooks, conference proceedings, reports, public reports of organizations as well as doctoral theses. Multiple sources applied include government norms and publications. Literature was derived from
various scientific databases, such as ScienceDirect, Wiley Online Library, IEEE, Google Scholar, Statista, EBSCO, SpringerLink, Emerald Journals and Scopus.

The input data of the LCOM calculations for electric aviation and hydrogen fuelled aviation are conditionally reliable. As electric and hydrogen aircraft do not exist in relevant scales that are required for most short- and long-range commercial flights, real flight test data and actual mission deployment data is not available and cannot be utilized for analysis. For instance, multiple studies do not consider capital costs of electric aircraft due to major uncertainties (Isikveren et al., 2016, p. 15; Brelje and Martins, 2019, p. 14). Instead, assumptions for cost data are derived from multiple studies that performed relevant modelling of all-electric and hydrogen fuelled flights. Hence, the results can only be as reliable as the assumptions made for input data.

The results of LCOM calculations are checked for sensitivity to changing input parameters. Overall reliability can be confirmed for the input parameters capex and carbon cost for all alternatives. Limited reliable is the parameter opex which showed an LCOM rise of 11% for hydrogen, 13% for electric and 15% for kerosene and biofuel when the input was increased by 20%. Moreover, limited reliable is the parameter fuel cost for hydrogen which showed 11% increase of LCOM at 20% increasing input parameters. For all other input parameters, the reliability test was positive. Thus, consistent findings are reached, and reliability proven.

The assumptions and concluding analysis concerning the criteria tree of the following AHP have been cross-checked with airline representatives, airport environmental department, manufacturer representatives and solar economy and innovation management researcher. From these discussions in dialogue, feedback was derived and integrated in the development of criteria. After careful considering of the inputs, criteria and sub-criteria were amended. Thus, reliability of AHP results is assumed.
4. Cost comparison

It is important not only to airlines, but to global governments to have zero emission technologies at lower operating costs available in order to reach the goals set in the Paris Agreement. This supports the air mobility of an even larger share of the world’s population and contribute of global economic development. In the consecutive cost comparison, all monetary values are expressed in US Dollars as this currency is commonly applied in aviation. All conversions from Euro to US Dollars are made utilizing the average exchange rate of the precedent five years of 1.2 (ECB, 2018). Solely for exemplary visualization, analysis and argumentation purposes Euro values are not converted.

4.1. Cost Components

In order to analytically compare the costs of the different alternative aircraft propulsion technologies, the main cost components of airlines need to be discussed. These are essential for a successful implementation of the technology besides several other key criteria.

The economic performance of airlines depends on various external factors and global economic trends as it is operating largely beyond borders. Main cost components of airlines are fuel, maintenance, labour and airport services cost (Camilleri, 2017, p. 3). During the last ten years, fuel costs made up 29% of airlines expenses (Heshmati and Kim, 2016, p. 57). Thereby, the kerosene price is directly influenced by the crude oil price and rises to the same extent as the oil price develops.

Figure 40: Long-term crude oil and jet fuel price development (IATA, 2019)
The kerosene price is overall 20% higher than the crude oil price, varying between $40-$140 per barrel within the last five years. In May 2019, price of jet fuel was $0.667 per kg (IATA, 2019).

The cabin crew creates a large part of value created by airlines and thus, besides fuel costs, labour takes a big part of the cost structure of airlines (Heshmati and Kim, 2016, p. 61). As numerous wage-improving initiatives are currently carried out by labour unions, cost of labour tends to increase in the future. Nonetheless, the amount of required cabin attendants and pilots is likely to remain at the same level despite introducing new aircraft technology and models into service. Hence, this part of the cost structure of airlines is not further analysed.

Airlines are largely impacted by externalities. Positive ones such as increasing tourism, development of emerging countries and globally rising GDP are some of the many reasons for the high growth rates in global aviation (Heshmati and Kim, 2016, p. 64). On the other hand, negative external costs are a major threat for airlines, such as costs from noise pollution, local air quality at airports and GHG emissions. The latter will have significant price in the future, due to the future mandatory participation of aviation in ETS and possible carbon taxes.

4.1.1. GHG emission costs

When it comes to carbon pricing, an international carbon pricing system and ETS is not existing yet (Ramstein et al., 2018, p. 33). Nevertheless, in Article 6 of the Paris Agreement, all parties are required to ratify their carbon emission reduction in NDCs which is a first step towards a global ETS. The CORSIA scheme for aviation will be one of the first global ETSs. Furthermore, there has been a variety of regional ETS systems implemented during the last 15 years, covering ca. 15% of overall GHG emissions. Most significant are the EU ETS, Japan Carbon Tax, Korea ETS and the planned China ETS which is expected to start in 2020.

Since aviation was included in the EU ETS in 2012, airlines registered in the participating countries need to report their GHG emissions and purchase emission allowances. Nonetheless, in 2018 airlines received free allocation for ca. 47% of their emissions. For the remaining part of their emissions, airlines are required to buy emission allowances which where historically at a very low level and thus not considered to be of any effect.
It can be seen that after the implementation of the EU ETS scheme the price of emission allowances decreased continuously. This was mainly due to an oversupply of free allocation of allowances. The low prices from 2012 through 2016 made the system ineffective. In the following example the emission costs of the Ireland-based airline Ryanair are analysed. In 2018, the airline was the tenth largest polluter of GHG emission within the ETS. Only coal power plants emitted more GHGs. The carrier had to buy allowances for €8.92 million in 2013 and for €20.5 million in 2016. In 2018, already €84.5 million are due for carbon costs.

In proportion to the revenues of the carrier in respective years, these costs represent only a very minor share. However, it is rising due to more restrictive limitation of free allocation. How much the carbon costs account per pkm is in more detail analysed in the LCOM calculations.
On a global scale, the prices of ETS and carbon taxes varied widely depending on the particular scheme. An overview can be found in Appendix III. The low prices of most of the schemes, such as the Chinese pilots, Japan, California and the EU of under $20 per tonne CO$_2$eq are not sufficient to limit global warming to the extent agreed in the Paris Agreement. Only few carbon taxes and ETSs, such as the initiatives of France, Finland and Sweden, reach carbon prices over $50 per tonne CO$_2$eq which is considered to be at the minimum required to reach agreed climate goals (Ramstein et al., 2018, p. 22).

In order to evaluate and decide about future alternative propulsion technology, the assumptions for the prospective development of GHG emission allowances are crucial. According to Breyer et al., the prices for GHG emissions will continue to rise over the coming decades in the following extent.

![Figure 43: Price trend of GHG emissions allowances, adapted from (BNEF, 2015; Breyer et al., 2018, p. 523)](image)

In May 2019, the carbon emission allowance had a price of 25.38€/t CO$_2$eq which is already relatively close to the predicted level of 28€ in 2020. The prices will continue to rise and from 2040 on a steeper rise is predicted due to the agreed achievement of zero carbon emissions in 2050.

4.1.2. Biofuel cost

One of the main reasons why biofuels have not yet been widely implemented in aviation is their higher price. Even without accounting production costs, already the feedstock is more expensive than kerosene. In 2016, palm oil which is used in HEFA biofuels costed $0.45/l whereas jet fuel was available for a price of $0.25/l (IRENA, 2017, p. 6). EU published a study stating that a $1800 premium on kerosene would be required to reach competitive bio
jet fuel prices (EC, 2013, p. 5). Palm oil based HEFA is overall the cheapest available option of biofuel, nonetheless it is not the one with the lowest GHG emission reduction potential.

Price gap is difficult to close when the oil price stays low as $50 per barrel, or $0.36/l. In April 2016, the prices of vegetable oils as feedstock exceeded the price of kerosene significantly.

Figure 44: Prices of vegetable oils for biofuel production (IRENA, 2017, p. 36)

De Jong describes the necessity of a carbon emission price of at least $200/t CO\textsubscript{2}eq in order to mitigate the GHG emissions. This study points out that even if the successful implementation of the CORSIA raises fossil fuel prices, yet biofuel production costs must be reduced, and subsidies need to be implemented to make it economically more viable for airlines to actually reduce emissions by introduction of biofuels instead of buying emission allowances.

Recently, International Energy Agency published a new price estimation for biofuels. HEFA based bio jet fuel ranges between $0.75/l and $1.60/l (IEA, 2018a). Hence, an average bio jet fuel price of $1.18/l is assumed in the following LCOM calculations.

4.1.3. Electric propulsion cost

Overall, in the principle of electric propulsion, the location of the energy generated to propel the aircraft is shifted from airborne as it is performed in current combustion engines, to the
Ground before charging swappable batteries. This offers a significantly wider range of energy generation technology that offers more possibilities and a lower price than inflight fuel burn. The cost of electric propulsion fuel is the respective electricity price. When considering GHG emission of electric flight, the source of electricity is vital. In order to reach zero GHG emissions in 2050, a 100% renewable electricity supply is assumed. Renewable electricity prices vary dependent on the method and region of production. Based on the global and seasonal resource availability for combined wind and PV power plants, the electricity cost of this production method is chosen. The weighted average cost of electricity of such a plant is $0.05/kWh (Fasihi, 2016, p. 24).

Overall capex for electric aircraft is challenging to number as there is an essential lack of data. Only Plötner et al. consider it to be in the same extent as combustion engine aircraft (Ploetner, 2013, p. 8). However, batteries can be expensive, thus capex is expected to be higher. Opex is expected to decrease due to less moving parts and thus lower maintenance needs (Howse, 2005, p. 35; Gohardani, et al., 2011, p. 383; Hornung et al., 2013, p. 10; Wheeler, 2016, p. 1; Brelje and Martins, 2019, p. 9; Gnadt et al., 2019, p. 9). Other crucial factors influencing LCOM are electricity cost, battery cost and battery lifetime.

It is assumed that the required battery capacity of 800 Wh/kg for a 500-1500 km flight is reached. These would have a price of 88$/kg and a lifetime of 2000 cycles (Bradley and Droney, 2015, p. 58). Moreover, battery capacities in aviation cannot be calculated as to be used fully. Due to safety reasons, there needs to be always a reserve considered. Required end state of charge is discussed to be 20-30%. 20% represents a 30min discharge at a C-rate of 0.4, additional 10% of charge is recommended for extending the battery life and cycle life time (Vratny et al., 2013, p. 9; Gnadt et al., 2019, p. 12). Specific battery handling costs are considered to be equal as cargo handling cost (Isikveren et al., 2016, p. 15).

4.1.4. Hydrogen fuel cost

The fuel price of hydrogen varies substantially depending on which feedstock and which production method is used. The main cost component of hydrogen production is the required electricity (Züttel, et al., 2008, p. 162; Mazloomi and Gomes, 2012, p. 3028). In 2001, Klug and Faass argue that the fuel price of tax-free mass produced liquid hydrogen from renewable energy resources would be cost-competitive of taxed gasoline or diesel (Klug and Faass, 2001, p. 253). As kerosene is yet tax-free, liquid hydrogen is thus not cost-competitive when
comparing fuel cost genuinely. Nonetheless, the expected increase in GHG emission pricing is awaited to have a higher influence on the cost competitiveness of fossil fuels.

Regarding specific fuel costs of hydrogen, many varying cost calculations are performed. EC states that hydrogen costs may range between $1.02-1.68/kg (EC, 2003, p. 62). IEA predicts most optimistically hydrogen costs of $0.90/kg (IEA, 2006, p. 18). Teichmann et.al. assess the price for hydrogen stored in Liquid Organic Hydrogen Carriers in Iceland at $2.30 per kg ($0.071 per kWh) (Teichmann, Arlt and Wasserscheid, 2012, p. 18129). Nevertheless, natural gas is used as feedstock which causes a production of 9.3kg CO₂ per kg produced hydrogen. Thus, this technology is not applicable for a zero GHG emission scenario.

Another price calculation is done by Stadler. He designates a price of $6.91 per kg of \( LH_2 \) (or $0.2073 per kWh) when utilizing the most proficient method of hydrogen production in a large scale based on renewable electricity (Stadler, 2014, p. 47). However, in this study, a Concentrated Solar Power (CSP) plant is assumed to deliver the energy. As CSP plants show low cost competitiveness compared to solar PV and integrated battery technology, hydrogen price reductions from cheaper electricity are possible (Breyer et al., 2018, p. 509). Moreover, CSP technology will not reach the rapid cost decline of e.g. hybrid PV-battery solutions (Breyer et al., 2017, p. 5). On the other hand, Jørgensen and Ropenus calculate a significant lower price of hydrogen from electrolysis using excess wind power in Denmark of $0.14-0.16/kg (Jørgensen and Ropenus, 2008, p. 5340). This very low value is not applied in the calculations, as excess a wind power scenario in that extent is not realistic for most of the global production sites.

Verstraete compared overall cost performance of liquid hydrogen fuelled aircraft. According to him, the effects of higher investment and maintenance costs of cryoplanes would still lead to lower direct operating costs as can be seen below.
Even at 50% higher investment and maintenance costs, hydrogen aircraft would be cost-competitive to kerosene fuelled aircraft.

Overall, the introduction of liquid hydrogen as jet fuel would offer a significant market potential for production of this gas of up to 100 million tonnes. This may lead to efficiency enhancement in production methods and consequentially fuel price reductions. Therefore, prices of kerosene and liquid hydrogen expected to equalizing in 2037 (EC, 2003, p. 12; Van Zon, 2018, p. 7). This is projected to be reached earlier in case governments implement regulatory frameworks or support market-based measures to support the price development of hydrogen.

### 4.2. Levelized Cost of Mobility

Common performance metrics utilized by carriers are cash operating cost that include varying flight costs, such as fuel, maintenance and crew costs and direct operating costs which further include investment costs (Brelje and Martins, 2019, p. 4). Another important performance indicator is cost per available seat mile which is levelized operating costs to a comparable number of seats and range. However, none of these cost performance indicators are suitable to compare alternative propulsion concepts. Thus, the principle of LCOM is applied in this study.

#### 4.2.1. Equations

In order to compare the alternatives to conventional kerosene driven combustion engine cost-wise, numerous types of costs need to be included. First, capital cost needs to be ascertained and normalized over the operational utilization period. Therefore, the two key figures
Weighted Average Cost of Capital (WACC) and Capital Recovery Factor (crf) are applied. WACC is a key performance indicator of minimum return on asset investment that is needed to satisfy the expectations of owners, investors and creditors (DePamphilis, 2018, p. 235). Therein, all costs of capital originating in debt and equity are proportionally weighted using the following formula:

\[
WACC = \frac{E}{E + D} \ast k_E + \frac{D}{E + D} \ast k_D
\]

where \(E=\)Amount of equity invested, \(D=\)Amount of debt invested, \(k_E=\)cost of equity/return on equity, \(k_D=\)cost of debt/interest rate.

Changes in WACC are dependent on return on equity, valuation and perceived risk (Child, 2017). Concerning investments in energy supply and infrastructure, a high number of public investors occur compared to other industries as realizing the project may have a higher priority than earning profit from the investment (Child, 2017). Alternatively, private investors usually expect a higher return on their investment as the energy investment competes with all on the market available investment opportunities. When simultaneously perceiving a high risk from the energy investments, even higher returns are expected.

The crf is a ratio applied to calculate the present value of an annuity which is a series of equal annual cash flows about a given length of time. By identifying the present worth of the investment, the actual cost of the financed system is evaluated (Plante, 2014, p. 165). The ratio is calculated in the following manner:

\[
crf = \frac{i \ast (1 + i)^n}{(1 + i)^n - 1}
\]

where \(i=\)discount rate and \(n=\)number of payments received.

The discount rate can be a given rate of interests, but WACC is more commonly defined by investors thus more accurately, the discount rate can be substituted by WACC. Moreover, in energy investments, payments are in general conducted annually for the lifetime of the project, hence crf is:

\[
crf = \frac{WACC \ast (1 + WACC)^N}{(1 + WACC)^N - 1}
\]

where \(N=\)lifetime of the project in years.
After having defined formulas for capital costs, integrating several other important cost components is necessary. Conclusive cost comparison is achieved by utilizing LCOM calculations for aircraft. The LCOM is based on the levelized cost for electricity (LCOE) which is broadly applied for comparison of power generation technologies. The applied methodology consolidates the overall cost of a specific system and makes the technology alternatives comparable on nominal prices. The specific LCOM of each technology is calculated as following:

\[
LCOM = \frac{\text{Capex} \times \text{crf}}{\text{Lifetime Pkm}} + \frac{\text{Opex}_f}{\text{fuel}} + \frac{\text{carbon} \times \text{GHG}}{\text{Pkm}}
\]

The results are expressed in $ per pkm. Thereby, LCOM includes investment/capital expenditures (capex) in $ per pkm, capital recovery factor (crf) as described above, operational expenditures (opex) in % of capex, fuel in $ per pkm, carbon as carbon price in $ per ton CO\text{2} equivalent, GHG as GHG emissions tonne CO\text{2} equivalent. The analysis is conducted in US Dollars as it is the currency commonly applied in aviation.

4.2.2. Assumptions

Capex is the market value of new aircraft which is significantly lower than given list prices. For short-range aircraft, the common models Airbus A320 and Boeing 737-800 are priced $39 million and $34 million respectively (Ackert, 2012, p. 28). Therefore, an average capex of $36.5 million for all combustion driven propulsion is assumed. For long-range aircraft, the common models Airbus A330-200 and Boeing 777-300ER are priced $86 and $155 respectively (Ackert, 2012, p. 28). This wider price range is making an assumption for a common capex more sensitive to error. Nonetheless, this uncertainty is existing for all cost comparisons and is hence negligible. An average capex of $120.5 million for long-range aircraft is assumed. Opex is equally assumed to be $0.09/pkm over all types of aircraft and consists mainly of maintenance, crew and fuel costs (Zuidberg, 2014, p. 87).

In order to calculate a correct crf, the assumed WACC and lifetime are important input parameters. The cost of capital for airlines is on average 7%-8%, thus a WACC of 8% is assumed (IATA, 2012, p. 13; Pearce, 2018, p. 3). The lifetime of aircraft is controversially discussed. Airbus proposes a service package with which the A320 life would be extended to 40 years, whereas Boeing published a study of average 27 years and the US bureau of transportation publishes values of around 30 years (Airbus, 2008; Jiang, 2013, p. 5; US
Due to application of conservatism, the average lifetime of an aircraft is assumed to be 30 years.

The alternative technologies are compared based on their cost performance according to different stage length. Eurocontrol, the air traffic control agency of Europe categorizes flights with ranges below 1500 km as short-range flights, below 4000 km as medium-range and above 4000 km as long range flights (Eurocontrol, 2011, p. 21). This is also applied in the initial market analysis of fuel consumption and GHG emissions of particular aircraft classes (Fig. 4). However, when regarding actual flight data, the majority of the globally most frequented routes are short-range flights.

Figure 46: Route range of globally most frequented routes, adapted from (OAG, 2019, p. 4)

Roughly half of the most common routes are below 1000 km and 91.97% are below 2250 km. Only one route (from New York to London) is a long-range route. Based on these two different range categorization possibilities, the range categories 500 km, 1500 km, 2500 km and 4000 km and above are applied in the calculations.

Moreover, assumptions to passenger count are made based on average seat capacity and load factor. Despite the aircraft utilized on these ranges offer higher seat capacity than the assumed passenger count, their average load factor is 75.18% (Zuidberg, 2014, p. 87). The average seat capacity applied by Park and Kelly comply with this load factor, thus the passenger count of 137, 159, 184 and 273 is applied (Park and O’Kelly, 2014, p. 141).
4.3. **Results**

Based on the formulated equations, the following crf will be applied for LCOM equations:

*Table 6: Crf calculation*

<table>
<thead>
<tr>
<th>WACC</th>
<th>%</th>
<th>8%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lifetime</td>
<td>years</td>
<td>30</td>
</tr>
<tr>
<td>crf</td>
<td>%/year</td>
<td>0.0888</td>
</tr>
</tbody>
</table>

Derived from these capital costs, the equations are applied for each alternative propulsion technologies assuming year 2020. First, kerosene driven combustion engine aircraft result in the following LCOM.

*Table 7: LCOM of fossil fuelled combustion engine in 2020*

<table>
<thead>
<tr>
<th>Component</th>
<th>Unit</th>
<th>Short Range</th>
<th>Long Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage length</td>
<td>km</td>
<td>500</td>
<td>1500</td>
</tr>
<tr>
<td>Passengers</td>
<td>count</td>
<td>137</td>
<td>159</td>
</tr>
<tr>
<td>Capex</td>
<td>$</td>
<td>36.50</td>
<td>36.50</td>
</tr>
<tr>
<td>Opex fix</td>
<td>$/pkm</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>Fuel cost</td>
<td>$/pkm</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Carbon cost</td>
<td>$/pkm</td>
<td>0.0033</td>
<td>0.0027</td>
</tr>
<tr>
<td>LCOM</td>
<td>$/pkm</td>
<td>0.12</td>
<td>0.11</td>
</tr>
</tbody>
</table>

It can be seen that besides regional routes, this form of propulsion shows very modest cost on all ranges in the near future. Only for long ranges it is slightly higher due to larger aircraft required that are related to higher capex. Carbon cost remains low as it is expected that emission certificates will not experience a strong price increase in the precedent year.

The first alternative propulsion, biofuel, results in the following LCOM.
Table 8: LCOM of HEFA-SPK based biofuel blend in 2020

<table>
<thead>
<tr>
<th>Component</th>
<th>Unit</th>
<th>Short Range</th>
<th>Long Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage length</td>
<td>km</td>
<td>500</td>
<td>1500</td>
</tr>
<tr>
<td>Passengers</td>
<td>count</td>
<td>137</td>
<td>159</td>
</tr>
<tr>
<td>Capex</td>
<td>million $</td>
<td>36.50</td>
<td>36.50</td>
</tr>
<tr>
<td>Opex fix</td>
<td>$/pkm</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>Fuel cost</td>
<td>$/pkm</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Carbon cost</td>
<td>$/pkm</td>
<td>0.0022</td>
<td>0.0018</td>
</tr>
<tr>
<td>LCOM</td>
<td>$/pkm</td>
<td>0.12</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Hereby, a 50% blend of HEFA-SPK based biofuel blend with kerosene is assumed. This type of biofuel is available in large-scale, certified by ASTM and reveals significant GHG emission reduction potential. However, the lower emission cost cannot outweigh the higher fuel price by 2020, which leads to increased LCOM of biofuel compared to kerosene.

Next, the LCOM of all-electric aircraft is presented. It is noted that in 2020 there will be no all-electric passenger aircraft in relevant scale be on the market. Thus, the calculation is performed for a 2035 scenario when numerous electric aircraft are expected to be developed.

Table 9: LCOM of all-electric aircraft in 2035

<table>
<thead>
<tr>
<th>Component</th>
<th>Unit</th>
<th>Short Range</th>
<th>Long Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage length</td>
<td>km</td>
<td>500</td>
<td>n.a.</td>
</tr>
<tr>
<td>Passengers</td>
<td>count</td>
<td>137</td>
<td>159</td>
</tr>
<tr>
<td>Capex</td>
<td>million $</td>
<td>36.50</td>
<td>36.50</td>
</tr>
<tr>
<td>Opex fix</td>
<td>$/pkm</td>
<td>0.08</td>
<td>0.08</td>
</tr>
<tr>
<td>Electricity cost</td>
<td>$/pkm</td>
<td>0.0231</td>
<td>0.0086</td>
</tr>
<tr>
<td>Carbon cost</td>
<td>$/pkm</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>LCOM</td>
<td>$/pkm</td>
<td>0.11</td>
<td>0.10</td>
</tr>
</tbody>
</table>

It can be seen that lower opex due to less maintenance needs and projected low renewable electricity cost makes this alternative propulsion technology cost-competitive on regional and short ranges. Despite projected future advancements in battery energy density of up to
2000 Wh/kg, as assumed in the study of Bauhaus Luftfahrt, electric propulsion will only be available on regional and short-range routes up to 1667 km. Longer ranges are not applicable.

The third alternative, hydrogen fuelled aircraft are feasible for all ranges, but are not expected to enter into service before 2050. The results of their LCOM can be found below.

Table 10: LCOM of liquid hydrogen fuelled aircraft in 2050

<table>
<thead>
<tr>
<th>Component</th>
<th>Unit</th>
<th>Short Range</th>
<th>Long Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stage length</td>
<td>km</td>
<td>500</td>
<td>1500</td>
</tr>
<tr>
<td>Passengers</td>
<td>count</td>
<td>137</td>
<td>159</td>
</tr>
<tr>
<td>Capex</td>
<td>$</td>
<td>40.15</td>
<td>40.15</td>
</tr>
<tr>
<td>Opex fix</td>
<td>$/pkm</td>
<td>0.09</td>
<td>0.09</td>
</tr>
<tr>
<td>Fuel cost</td>
<td>$/pkm</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Carbon cost</td>
<td>$/pkm</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>LCOM</td>
<td>$/pkm</td>
<td>0.12</td>
<td>0.11</td>
</tr>
</tbody>
</table>

It can be seen that liquid hydrogen fuelled aircraft are cost-competitive on all ranges, but specifically on longer ranges. This is mainly due to their higher efficiency that outweighs heavier empty weight due to hydrogen storage on board. Capex is expected to be higher for this technology, whereas close to zero carbon costs arise due to their significantly reduced emission intensity.

Throughout all alternative technology, opex takes a major share of LCOM. The share of fuel cost, carbon cost and capex is modest compared to possible changes in opex. However, as only minor alternances between the opex of different technology are recognized, it does not influence on the superiority of any alternative.

Aggregated, the cost performance of the different alternatives in 2020 and future price and performance developments become apparent.
Based on LCOM it was found that in 2020, kerosene remains the most cost-competitive option for aircraft propulsion on all analysed ranges. Only for regional flights of 500 km and 137 passengers, biofuel and electric can reach the same LCOM than kerosene of $0.12/pkm. Electric aircraft are conditionally included in 2020 for regional routes, as the Wright Electric aircraft is expected to enter into service in 2027. Different results are anticipated in 2035.
Due to expected price increases in emission certificates, electric aircraft become cost-competitive on ranges of 500 km and biofuel aircraft become on ranges of 4000 km. Biofuel costs are expected to decrease whereas emission costs are anticipated to increase which make kerosene less cost-competitive. Yet, jet fuel remains the least cost option on ranges of 2500 km. On short ranges up to 1500 km, electric aircraft have the lowest LCOM of $0.10/pkm. In 2050, further price developments are leading to a different scenario.

![Figure 49: LCOM of alternatives in 2050](image)

It can be seen that on all ranges, kerosene is the costliest option in 2050. For this time horizon, the introduction of liquid hydrogen aircraft in scale is projected. This technology has the lowest costs for 4000 km range of $0.14/pkm and for 2500 km range of $0.11/pkm mainly due to the absence of notable emission costs and advanced LH$_2$ production at moderate cost. For 1500 km ranges, electric propulsion remains the cheapest option with a LCOM of $0.10/pkm. Likewise, it shows the same LCOM of $0.12/pkm on 500 km ranges as liquid hydrogen.

A summary on the least cost options on the ranges 500 km, 1500 km, 2500 km and 4000 km for the time horizons 2020, 2035 and 2050 can be found below.
It can be concluded that in 2020, kerosene remains the main propulsion technology on all ranges. From 2035 on, electric aircraft enter into service and are cost-competitive on regional and short ranges of 500 km and 1500 km. Due to increasing emission cost, biofuel blends become cheaper than kerosene on medium ranges of 2500 km. In 2050, the first liquid hydrogen fuelled aircraft are expected to enter into service which are cost-competitive on long ranges. Overall, biofuels remain a cost-competitive option to lower the kerosene consumption and related emission intensity of aviation on varying ranges within the next 30 years. Particularly in case liquid hydrogen aircraft are not mature for being deployed by 2050, biofuels and especially synthetic fuels remain the only option to achieve low emission long range flights at current cost levels.
5. Technology selection model

Following the quantitative analysis of the most favourable propulsion technology based on cost data, further qualitative criteria play a role in selecting the superior technology. Due to limited scope of this thesis, the following analysis of alternative propulsion technology based on their overall suitability and sustainability is limited to the time horizon of 2020.

In previous literature multiple methodologies are presented to help select a technology over others. Among others, there is the Technology Selection Model, Strategic Grid, Technology Selection Criteria, PESTEL, Proactive Technology Selection Model and Cost-Benefit Analysis (Breiing and Knosala, 1997, p. 228; Cochran, 2009, p. 2; Shen et al., 2010, p. 159; Hung and Lee, 2016, p. 193). Each of them has a specific benefit and usage for given technology comparison frameworks. In the case of selecting alternative propulsion technology, there are numerous heterogenous criteria influencing a validated assessment. On the one hand, there are many qualitative criteria such as security and technology readiness and on the other hand, there are quantitative criteria such as LCOM and GHG emission reduction potential. Thus, a flexible, hybrid approach is needed.

One possible methodology to apply is Quality Function Deployment (QFD). This method focusses on the voice of the customer when proposing a technology/concept choice and analyses in detail customer needs, expectations and priorities, thereby, a two-dimensional matrix is used to define the best choice (Cohen, 1995, p. 11). Overall, QFD cannot be applied to the existing concept prioritization with optimal results, as for each propulsion technology there are proper quality requirements and characteristics missing, but more objective selection criteria that need to be assessed. Hence, another technology selection model, the AHP is presented.

5.1. Analytic Hierarchy Process

This technology rating and concept selection model is applied mostly for evaluation of relatively simple systems with less depth of details (Feldhusen and Grote, 2013, p. 395). It is a structured technique for organizing and analysing complex decisions and is especially favourable to be applied in this case as it allows qualitative as well as quantitative evaluation (Gupta et al., 2015, p. 212). Therefore, it is qualified to be applied in this study.
In general, there is one goal to be achieved by selecting the most favourable choice from a set of n alternatives (Brunelli, 2015, p. 3). In this application the fundamental decision to be taken can be represented like this:

![Diagram of alternative aircraft propulsion with Biofuel, Electric, and Hydrogen options](image)

*Figure 51: Evaluating alternatives in relationship to an overarching goal*

Hereby, Kerosene is not included as alternative, as only the performance of different propulsion technologies to replace kerosene are to be compared and their favourability over each other is rated. Often it is not obvious on the first sight which alternative is the most likely one to be chosen as there are multiple criteria to be compared and evaluated before the preferred option can be pointed out. This is exceeding the cognitive apprehension of humans in most of the cases and thus, a way to overcome this complexity is needed. A possibility to do this is to pairwise compare the alternative solutions in a matrix:

\[
A = \begin{pmatrix}
1 & x_{12} & x_{13} \\
1 & 1 & x_{23} \\
x_{31} & x_{32} & 1
\end{pmatrix}
\]

Comparisons are done for example like this: Alternative 1 is rated to be equally or same important compared to alternative 2. A ranking scale for criteria is applied to specify the degree of importance.

<table>
<thead>
<tr>
<th>Value of $x_{ij}$</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Equal importance</td>
</tr>
<tr>
<td>3</td>
<td>$i$ is slightly more important than $j$</td>
</tr>
<tr>
<td>5</td>
<td>$i$ is more important than $j$</td>
</tr>
<tr>
<td>7</td>
<td>$i$ is strongly more important than $j$</td>
</tr>
<tr>
<td>9</td>
<td>$i$ is absolutely more important than $j$</td>
</tr>
</tbody>
</table>

Moreover, values in between these scales, such as 2, 4, 6 and 8 may be used in case of indecisiveness. Especially when it comes to complex contexts, the pure choice between alternatives is not sufficient, but different criteria and related sub-criteria need to be
considered. In order to visualize these, a criteria tree is presented (Shi and Lai, 2013, p. 59). A larger scale figure of the criteria tree can be found in Appendix II.

Figure 52: Criteria tree for alternative aircraft propulsion selection

Multiple criteria clusters containing related sub-criteria need to be assessed before being able to choose from the set of alternatives in order to accomplish the overarching goal “alternative aircraft propulsion”. Generally, each cluster has related sub-criteria. The criteria were developed after consulting several experts in aviation industry, thus were established from airline, airport, manufacturer and research point of view. Main criteria are Cost, Emissions, Readiness and Safety. The respective sub-criteria are diverse and encompassing and lead to a coverage of the three spheres of sustainability, letting the decision be an economic, social and environmental sustainable choice (Rodriguez et al., 2002, p. 8).

When applying the methodology, especially the comparison of the sub-criteria needs to be done very systematic and with peculiar caution (Teknomo, 2006). In a first step, all criteria are listed in a table and pairwise compared according to their scale of preference.

Figure 53: Pairwise comparison of sub-criteria based on their importance scale
The scaled matrix is now being normalized and summed over the rows in order to obtain the priority vector e.g. \( w = (0.071; \ldots; 0.425) \). Now, there is certainty about which criteria has the largest importance on the choice of alternatives and based on the ascertained hierarchy, the weighting of the criteria is derived a rank of the criteria can be implemented.

In a second step, each of our choice alternatives, biofuel, electric and hydrogen are pairwise compared according to their performance in each selection criteria.

<table>
<thead>
<tr>
<th>Capex</th>
<th>Biofuel</th>
<th>Electric</th>
<th>Hydrogen</th>
<th>Priority vector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biofuel</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electric</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydrogen</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Figure 54: Pairwise comparison of the technology's performance according to criteria*

With respect to the criteria capex, each alternative has a different performance. For example, biofuel has a higher performance in Capex than hydrogen. This step is repeated for all criteria and corresponding priority vectors are calculated. It is recommended that the consistency of both pairwise comparison techniques are checked by computing a consistency index and ratio.

Finally, the overall composite weight of each alternative choice is calculated by summarizing weights of step one and step two. The overall weight is computed as normalization of multiplication between weight and priority vector as demonstrated below.

Biofuel = (weight of criteria 1) * (priority vector of biofuel with respect to criteria 1) + ... +

= composite weight

Electric = () * () + ... += composite weight

Hydrogen = () * () + ... += composite weight

The ranking of the composite weight is the outcome of the overall goal to select between alternative aircraft propulsion. The highest weight is the most preferred alternative etc. Moreover, it can be concluded how much more preferred a choice is over the other by comparing the composite weights. E.g. biofuel is 3.4 times more preferable than electric. Likewise, the overall consistency of hierarchy of the alternatives is recommended to be calculated.
5.2. Results

In the following the outcomes of applying the AHP to this study are presented. First, the sub-criteria were pairwise compared and the priority vector for each criterion has been derived.

![Figure 55: Results of pairwise comparison of sub-criteria](image)

It can be seen that the sub-criteria are divergently important for the overall decision for a propulsion alternative. In-flight safety has been rated as the most important criteria, followed by technology readiness and GHG emission reduction potential. The least important criteria are noise, capex and fuel handling. However, the compliance with all criteria are prerequisites for a successful certification and implementation of the propulsion concept.

In the next step, the three alternatives are rated by their performance of fulfilling each criterion.

![Figure 56: Results of pairwise comparison of the technology's performance according to criteria capex](image)

As example, biofuel shows nearly 2 times as high performance in capex terms as electric and ca. 3.5 times higher performance than hydrogen. This step is repeated for each sub-criterion in order to compute respective priority vectors.
Finally, each priority vector of each sub-criteria and the respective priority vector of the performance of the alternatives in this sub-criterion are multiplied and added up to an overall composite weight.

![Figure 57: Results of the overall composite weight of each alternative](image)

<table>
<thead>
<tr>
<th></th>
<th>Cost</th>
<th>Emissions</th>
<th>Readiness</th>
<th>Safety</th>
<th>Overall composite weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biofuel</td>
<td>5.08%</td>
<td>1.91%</td>
<td>15.57%</td>
<td>5.98%</td>
<td>28.53%</td>
</tr>
<tr>
<td>Electric</td>
<td>11.09%</td>
<td>9.05%</td>
<td>10.61%</td>
<td>15.57%</td>
<td>46.33%</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>6.33%</td>
<td>6.93%</td>
<td>7.41%</td>
<td>6.36%</td>
<td>27.03%</td>
</tr>
</tbody>
</table>

It can be seen that electric propulsion is the technology to be chosen according to various qualitative criteria. With 46.33% overall composite weight it is 1.8 times more favourable than biofuels and synthetic fuels and 1.7 times more favourable than hydrogen fuelled aviation. This is due to the good performance of the technologies in the criteria safety, cost and emissions. Yet, biofuels are the most mature technology which makes it the second choice. Hydrogen does not represent a sufficiently mature technology and does not have major superiority in other criteria which makes it slightly less favourable as biofuel.

The assessment of the performance of the alternatives in the criteria are based of the time horizon of 2020 and remain sensitive for changes of the technologies’ performance in the criteria over time. In case technology readiness is improving for electric and hydrogen, these alternatives become more attractive. Similarly, in case the emission intensity of biofuel decreases, its favourability increases. A more detailed overview of the results of AHP can be found in Appendix IV.
6. Discussion

Alternatives to kerosene-based aviation have been presented and reviewed on the basis of cost, emissions, readiness, safety and overall sustainability. Not every technology is ready for usage in the near future. Significant research and development activity is required to bring electric and hydrogen aircraft to maturity. However, each of the alternatives present advantages and disadvantages on different ranges and passenger capacity. Not just mature and cost-competitive technology play a significant role in achieving an energy transition in aviation, but also adequate infrastructure and future-oriented airlines willing to invest in novel technology. A superior technology can only be recommended based on comprehensive comparison.

Commonly, conventional jet fuel has played an exclusive role in propelling aircraft. Kerosene has an outstanding energy density and represents a safe and reliable energy source for various kinds of aircraft missions. Aircraft and respective gas turbines have been exhaustively optimised for this type of propulsion and offer elaborated technology at comparably low cost. In addition, as liquid fuel, it can be stored and transported without difficulty utilizing a globally existent infrastructure. Nonetheless, kerosene derived from oil is a finite resource with high GHG emissions. The tendency of rising prices and dramatic volatility in fuel prices contribute mainly to large year-on-year variations in the expenses of airline and make airlines consider significantly restructuring their fleets in order to become less abundant from fuel price volatility (Hileman et al., 2008, p. 3; Heshmati and Kim, 2016, p. 55). Price fluctuations in oil prices are mainly due to political, social or economic instability in oil-exporting countries, thus gaining independence from single countries is of major advantage for the profitability of airlines.

In general, the LCOM of kerosene is predicted to rise in the future due to higher carbon costs. Only by considering the emission certificate price enhancements, it becomes less competitive compared to other alternatives. A possible introduction of a global carbon tax would rise the LCOM of kerosene in a higher extent than expressed in the LCOM calculations. Furthermore, continuing with the business-as-usual scenario of kerosene-based aviation will lead to a gap of 1,039Mt CO₂ emissions by 2050 compared to a target of carbon neutral growth from 2020 onwards. When aiming to reach the goal of limiting global warming to 1.5°C, zero emissions by 2050 needs to be reached and the emission gap in
aviation is even larger. Per kg of kerosene burned, 3.7kg CO₂eq emissions are released. All discussed propulsion alternatives offer significant lower emission values and thus support closing this gap.

Bio- and synthetic fuels are qualified to act as most realistic alternative to kerosene in short and medium-term. It is implicated to improve the emission intensity of aviation sector by investments in biofuel research and infrastructure so that they can play a main role in reducing carbon emissions in aviation (IATA, 2018a, p. 34; IRENA, 2019, p. 46). As hydrogen and electric aircraft are currently still under development and yet to be produced in scale, these alternatives are qualified to replace carbon fuel combustion engines only after 2035. Thus, in short term, the introduction of biofuels offers the possibility to reduce the impact of aviation on climate change in the most realistic way. Sugarcane based ATJ biofuels, used cooking oil based HEFA-SPK as well as FT fuels have the potential to reduce emissions of aviation by 75%, 69% and 100% respectively when applied as single blend. However, to date, only a 50:50 blend of bio- and synthetic fuels are certified to use in commercial flight which reduces the emission reduction potential of biofuels by half. Unless a certification of 100% bio- and synthetic fuels is approved, emissions of aviation can be reduced by half at maximum.

Moreover, the application of biofuel as alternative to kerosene is dependent on several factors. First, crude oil prices are yet low and support the use of kerosene over biofuels. As can be seen from Ryanair’s emission cost, despite rising share of emission costs, these account for just a minor fragment of the airline’s revenues. Until 2027, the offsetting scheme CORSIA will most-likely continue to provide airlines with cheap CO₂ certificates that compete with carbon emission reduction from the use of more expensive biofuels (Kaltschmitt and Neuling, 2018, p. 758). Thus, a more effective carbon pricing in form of global ETS or jet fuel tax is required imperatively. Moreover, fossil fuel subsidising is to be removed. The global responsibility to limit climate change is key in order to prevent that growth is outpacing safety to live on earth. Following the proposed measures could lead to significant changes in fuel utilization. By 2035, it is projected that 31% of aviation’s fuel mix consist of biofuels, natural gas and electricity (McKinsey, 2019, p. 19). Congruently, Lufthansa targets to substitute 5% of its kerosene consumption by synthetic fuels in 5 years.

The second alternative, electric propulsion, is highly unlikely to become mature before 2035. The variants hybrid electric and turboelectric propulsion offer interesting transitory
technologies that help achieve maturity of electric devices in the near future. Nevertheless, none of these two propulsion alternatives reaches significant emissions reduction potential in the long run, thus, they are not qualified to act as main alternative for kerosene driven combustion engines (Epstein and O’Flarity, 2019, p. 10; Gnadt et al., 2019, p. 3). This can solely be reached by all-electric aircraft. Nevertheless, only if significant battery energy density improvements are achieved in the coming years, electric aircraft of relevant passenger count and range up to 1500 km are able to enter into service in medium term. Ranges above 1667 km are not considered as feasible even by the most optimistic studies due to the lack of airborne electricity storage for flights with longer ranges (Gnadt et al., 2019, p. 15). Nonetheless, the possibility remains that Wright Electric in combination with Easyjet develops a small regional electric aircraft which would be mature to enter into service in 2027. Despite this, to date, there is no electric aircraft in the size of a standard single-aisle aircraft with passenger capacity of around 150 existing. Furthermore, electrical devices, such as engines and transformers that could be applied in electric aircraft are missing.

However, for most regional and short-range flights, electric aircraft present the lowest cost option from 2035 onwards. This is mainly due to their expected lower maintenance cost by ca. 4% and the feasibility of electricity supply by renewable energy sources at low cost of ca. $0.05/kWh. However, this is mainly dependent to large regional variations. For a successful implementation of electric aircraft, a more detailed analysis of local feasibility of powering electric aircraft by renewable electricity at low cost is recommended. Nevertheless, electricity cost is less fluctuating and easier to predict than jet fuel cost which is dependent on the oil price (U.S. EIA, 2017).

In case the power demand is sourced from renewable electricity, this alternative is emitting zero GHGs from usage which is the most important advantage of this technology. In case the current grid electricity is utilized to charge electric aircraft, their emissions might even surpass kerosene driven combustion engines by up to 11% (IEA, 2017, p. 650; Epstein and O’Flarity, 2019, p. 9). The associated increase in renewable electricity demand could be solved by investing in combined solar PV and wind power plants supplying airports that are financed by emission offsetting efforts and carbon taxes. Other low-cost renewable electricity sources are solar PV single-axis tracking, hydro power and onshore wind power plants.
Supporting electric propulsion would thereby signify becoming independent from oil exporting countries and support local development and creation of jobs. This signifies that electric propulsion is socially sustainable. Similarly, it can be recognized by analysing the results of the AHP. Electric propulsion is the first choice of alternative propulsion technology from a thorough qualitative assessment of alternatives. Especially its high performance in safety, GHG emission reduction and cost is making it an attractive option in order to decarbonize aviation. Nonetheless, technology readiness is the key limiting factor and increasing research and development activity should be supported. Without significant achievements in increasing battery energy densities, only very short ranges can be covered by electric aircraft. Furthermore, it should be considered separately how electric aircraft perform in a life-cycle analysis with special focus on sourcing, production and recyclability of applied batteries.

The third option to be discussed is liquid hydrogen fuelled aviation. It is compatible for utilization in currently existing combustion engines and offers close to zero GHG emissions. Moreover, hydrogen can be produced from a large variety of feedstocks what is representing an unlimited resource availability (Mazloomi and Gomes, 2012, p. 3025). The main challenge remains its low voluminous energy density. Even in liquified form this gas is 4.2 times more voluminous than kerosene. New aircraft are required which include bulky tanks to store the voluminous gas. On the other hand, its weight is 2.8 times less which is significant in aviation. Nevertheless, the handing of the gas is challenging due to for liquification required cryogenic temperatures of minus 253°C. For commercial aviation based on liquid hydrogen, cylindrical tanks are required for energy storage and thus new aircraft design and adaption of manufacturing processes is necessary.

A drawback of liquid hydrogen aviation is the immature fuel production and related global fuel supply infrastructure which are responsible for comparatively high fuel cost. Zero GHG emission production methods, such as producing hydrogen via electrolysis is to date only responsible for 3% of global hydrogen production mainly as chemical raw material. Once the application changes towards a significant energy carrier, this ratio can change towards electrolysis using renewable electricity as power input (Züttel, et al., 2008, p. 163). Furthermore, a large-scale hydrogen production and its application as energy carrier in aviation would be associated with the advantage that low-cost renewable electricity production during off peak hours can be utilized.
What remains uncertain is the impact of higher water vapour emissions and related contrail formation of liquid hydrogen aircrafts on global warming. As there is no aircraft in scale existing that could be utilized for flight testing, the evaluation has to be done based on simulations. These reveal a positive impact on cryoplanes on global warming due to differing properties of contrail formation. Nevertheless, these results need to be supported by flight test data. Moreover, when including other costs than LCOM, such as social and environmental costs, hydrogen fuelled aviation is clearly the least cost option. According to Bicer and Dincer it has social and environmental costs of $0.04/tonne-km and kerosene $0.21/tonne-km (Bicer and Dincer, 2017, p. 10735). From the results of the AHP can be seen that liquid hydrogen propulsion is the least favourable option at current viewpoints, but close to the second option, biofuels. This is mainly due to its low technology readiness and higher capex and fuel cost. The performance in the safety criteria is same as in biofuels and liquid hydrogen aviation’s GHG emission reduction potential is clearly higher. Once the technology and fuel supply infrastructure becomes mature and the impact of related contrail formation is clarified, hydrogen is the recommended choice for long range aircraft.

Nevertheless, the large-scale production and certification of synthetic fuels are a key development opportunity that might make the research and development activities to develop liquid hydrogen aircraft unnecessary. Once a 100% synthetic fuel blend is certified by ASTM and considerable amounts of synthetic fuel can be produced at modest cost, this option is clearly the most recommended one for long range routes as existing aircraft models and supply infrastructure can be utilized.

Overall, the different alternatives are qualified in a varying extent to contribute to limit global GHG emissions of aviation. Lee et al. conclude from a long-term assessment of possible actions including technology improvements, realistic biofuel penetration and extension of existing market-based measures that a combination of these methods are most promising to close part of the GHG emission gap of aviation. However, these solely are not eligible to close the gap completely. Thus, the development of electric aircraft for short ranges and hydrogen fuelled aircraft or a 100% blend of synthetic fuel on long ranges shall be promoted intensively. An upward trend in research activity and publications is visible from quantitative literature review. Research activity in biofuels rose by 11% per year, in electric propulsion by 12% per year and in hydrogen fuelled aircraft by 13% per year. Promising outcomes are expected.
This may lead to a significantly more deviating aircraft fleet which is not recommended to maintain. Various different aircraft models and propulsion technology are avoided as scale effects cannot be used (Seristö and Vepsäläinen, 1997, p. 17; Zuidberg, 2014, p. 88). Therefore, despite some specific alternatives are more cost-competitive on certain ranges, it is suggested that airlines keep their fleet as uniform as possible in order to operate more cost efficient. Thus, deciding for the least amount of technology concepts that offer the highest GHG emission reduction potential is recommended. First changes in the fleet structure towards more fuel-efficient aircraft can be recognized, as recently the largest passenger aircraft program, the A380, was announced to be ceased mainly due to its high fuel consumption.

Overall, it will be very challenging to disrupt the energy transition of the aviation sector, as practises taking years and decades would need to be amended. Nevertheless, given the high amount of jet fuel burned each year world-wide, even minor improvements have a large buoyancy. Already low one-digit percentages of biofuels will have a significant impact on GHG emissions (Yilmaz and Atmanli, 2017, p. 1383). With regard to the pressing necessity to limit climate change, decision makers are required to act rapidly, as development of a completely new aircraft design is lengthy in time. Complete aircraft development and manufacturing infrastructure changes takes 30-35 years, thus changes in aircraft production will have an impact on the fleet only after this time frame (EEC, 2005, p. 103). Alternatively, research and development in synthetic fuel and efforts to support 100% biofuel blends are highly recommended to avoid the necessity of new aircraft design. In order to reach globally agreed climate targets, proactive decisions are required. Investing in hydrogen aircraft production, fuel supply as well as battery research is highly recommended in order to decarbonize the aviation sector. Furthermore, bio- and synthetic fuels are highly eligible to close the emission gap of aviation to a significant extent in the near future.

**Areas for further development**

Further research in the certification of 100% bio- and synthetic fuel blends has to be promoted and confirmed by significant flight testing of alternative fuels. In addition, the production capacities of bio- and synthetic fuels is required to be scaled up rapidly in order to be able to supply future demand of renewable jet fuel at low cost. Especially the production methods of synthetic fuel are to be improved as with low cost and globally available synthetic fuels the emission intensity of long-range flights could be reduced...
without difficulty. Furthermore, other alternative fuels, such as liquefied natural gas are recommended to be analysed. This fuel offers the possibility of thermal management benefits in a background of more electric aircraft and should be included in a thorough study of alternative aircraft fuels despite its lower energy density (Roberts, et al., 2015, p. 8).

When it comes to electric aircraft, further research is recommended in battery energy density which is the most limiting factor to achieve energy transition in aviation. Likewise, the development of electrical engines and drives to be applied in large scale in aviation is necessary. Moreover, the environmental sustainability of electric aircraft is suggested to be discussed further. A life-cycle analysis with special focus on sourcing, production and recyclability of applied batteries is recommended. Another important topic is the renewable electricity supply of a possible electric aircraft fleet on airports which shall be analysed in more depth. In addition, airline routines shall be analysed for possible changes towards supporting the use of electric aircraft. Reducing take-off power requirements by utilizing longer runways, reducing wing load or improving take-off high-lift systems are important measures to be discussed further.

Concerning hydrogen fuelled aviation, the effect of contrails of liquid hydrogen aircraft in flight testing is required to be determined. Studies performed and related simulations are leaving uncertainty due to the lack of a fully developed cryoplane. Similarly, the proposed design of cryogenic aircraft must be advanced and tested in small scale and later to be scaled up. When it comes to the application of hydrogen fuel cells, the complete APU system of aircraft shall be revised and tested for a shift towards hydrogen-based technology. As consequence, further research and testing concerning the application of hydrogen on-board would be supported. Furthermore, the supply of liquid hydrogen is suggested to be scaled up in order to meet demand in the long term. Further research should discuss the large-scale production method of hydrogen based on renewable sources.
7. Conclusion

In this study, cost-oriented means that limit the impact of aviation on the environment in the largest possible extent were discussed. Generally qualified to act as replacement of fossil fuel driven combustion engines are bio- and synthetic fuels, electric propulsion and hydrogen fuelled aviation. These alternatives were compared and ranked based on their performance in cost and sustainability terms.

Fossil fuels possess outstanding technical and economical features which make them ideal to be applied in aviation during the coming 15 years. Due to current low carbon cost from ETSs and the lack of a global jet fuel tax, they show the lowest LCOM on all ranges in the near future. Nevertheless, an alternative is to be found in order to comply with global climate targets. The concepts biofuel, electric and hydrogen propulsion are offering substantial GHG reduction potential and are in varying extent realisable and globally versatile.

Biofuels are most realistically to reduce the carbon footprint of aviation in short term as they can be applied in current aircraft models, fuel production facilities are existing, and they reach 34.5% GHG emission reduction potential compared to jet fuel. Furthermore, they have the lowest LCOM on ranges of 2500 km from 2035 on due to increasing carbon and fuel costs. Nevertheless, zero carbon emissions can only be reached by 100% blend of synthetic fuels and electric aircraft. Furthermore, kerosene remains the least cost option on long ranges of 4000 km and more until 2050.

Electric propulsion can achieve zero GHG emissions when powered by renewable electricity which is unlimited available globally. Nonetheless, electric aircraft are to date not existing in relevant size due to a significant lack of high battery energy density. First models are expected to enter into service on routes of 500 km in 2027 and of 1500 km in 2035. Longer ranges than 1667 km are highly unlikely to be feasible with electric aircraft in any time horizon. When being technologically mature by 2035, they represent the least cost option to close the emission gap of aviation on regional and short routes.

Likewise, hydrogen fuelled aircraft offer close to zero GHG emissions. The low weight of LH$_2$ makes this propulsion technology especially efficient on long ranges. However, they are not expected to enter into service before 2050 as a completely new aircraft model would need to be designed to store the voluminous gas at cryogenic temperatures. When being
developed, they show the lowest LCOM for ranges of 2500 km and 4000 km in 2050 due to the absence of carbon costs and moderate expected fuel cost. Besides utilizing hydrogen for propulsion, the deployment of hydrogen fuel cells in-flight and as ground power supply in APUs is highly recommended to lower GHG and noise emissions of airports.

From an overall sustainability point of view, the following set of qualitative criteria determines a justified choice of alternative propulsion technology: the cost criteria capex, opex, fuel cost and carbon cost; the emissions criteria GHG emission reduction and noise; the readiness criteria technology, infrastructure and resource availability as well as the safety criteria fuel handling and in-flight. According these criteria, electric propulsion is 1.8 more favourable to be chosen followed over biofuels and synthetic fuels and liquid hydrogen aviation. Electric propulsion shows strong performances in safety, cost and emission criteria, whereas its readiness is poor. Biofuels have a high technology readiness and moderate cost and safety performances. However, their performance in emissions is poor compared to the two other options. Hydrogen fuelled aviation shows good performance in emissions and moderate in safety and cost. Nonetheless, the technology is very immature and thus not yet capable of acting as alternative propulsion technology. Once technology readiness increases and carbon costs rise, electric and hydrogen propulsion become more favourable to achieve the 1.5°C constraint than biofuels. On the other hand, in case synthetic fuels in a 100% blend are certified and can be globally produced, this technology would be clearly more favourable to close the emission gap.

Finally, the energy transition of the aviation sector is of high self-interest. Global carbon taxes, voluntary denial of individuals to travel by air and rising insecurity about oil supply pose significant threats to future growth. Thus, the commitment and collaboration of airline management, manufacturers as well as governments is required in order to preserve sustainable market development of global aviation that is consistent with climate targets. Various cost-competitive options for decarbonizing fossil fuel-based aviation are qualified to be deployed in the near- to distant-future. It can be concluded that all discussed alternatives present a possibility to decrease dependence of aviation on fossil fuels, prevent rising cost for emission allowance certificates and close the gap to zero emissions from aviation by 2050. Now, a clear commitment to achieve energy transition in aviation is required, including significant investments in battery research, efforts in bio- and synthetic fuel certification and improvements of hydrogen and synthetic fuel production.
References


### Appendix I: Survey of all-electric aircraft models (Gnadt et al., 2019, p. 4)

<table>
<thead>
<tr>
<th>Type</th>
<th>Aircraft</th>
<th>Location</th>
<th>Seat Count</th>
<th>Range (miles)</th>
<th>Cruise Speed (kn)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>VTOL</td>
<td>AIS 2-500</td>
<td>Pohang, South Korea</td>
<td>2</td>
<td>162</td>
<td>120</td>
<td>Devel</td>
</tr>
<tr>
<td>VTOL</td>
<td>Airbus 3 Vahana Alpha</td>
<td>Santa Clar, CA, USA</td>
<td>1</td>
<td>26</td>
<td>110</td>
<td>Dev</td>
</tr>
<tr>
<td>VTOL</td>
<td>Airbus 3 Vahana Beta</td>
<td>Santa Clar, CA, USA</td>
<td>2</td>
<td>52</td>
<td>125</td>
<td>Dev</td>
</tr>
<tr>
<td>VTOL</td>
<td>Airbus 4 Vahana Alpha</td>
<td>Hamburg, Germany</td>
<td>5</td>
<td>114</td>
<td>183</td>
<td>Dev</td>
</tr>
<tr>
<td>VTOL</td>
<td>AMX, Vahana</td>
<td>New South Wales, Australia</td>
<td>2</td>
<td>162</td>
<td>136</td>
<td>Dev</td>
</tr>
<tr>
<td>VTOL</td>
<td>AXX MOD 2025</td>
<td>Norwood, MA, USA</td>
<td>4</td>
<td>62</td>
<td>130</td>
<td>Dev</td>
</tr>
<tr>
<td>VTOL</td>
<td>AXX MOD ONE</td>
<td>Norwood, MA, USA</td>
<td>5</td>
<td>57</td>
<td>130</td>
<td>Dev</td>
</tr>
<tr>
<td>VTOL</td>
<td>Aureon EVTOL (unmanned)</td>
<td>Miami, FL, USA</td>
<td>2</td>
<td>35</td>
<td>108</td>
<td>Devel</td>
</tr>
<tr>
<td>VTOL</td>
<td>Autogiro EX1400</td>
<td>Garching, Germany</td>
<td>2</td>
<td>108</td>
<td>54</td>
<td>Devel</td>
</tr>
<tr>
<td>VTOL</td>
<td>Autonomous Flight Y6</td>
<td>Shenzhen, China</td>
<td>2</td>
<td>70</td>
<td>64</td>
<td>Devel</td>
</tr>
<tr>
<td>VTOL</td>
<td>Carter Electric/Hybrid Air Taxi</td>
<td>Wichita, KS, USA</td>
<td>5</td>
<td>58</td>
<td>152</td>
<td>Dev</td>
</tr>
<tr>
<td>VTOL</td>
<td>Dream Aerospace (Aix)</td>
<td>Lagoa Beach, CA, USA</td>
<td>2</td>
<td>164</td>
<td>130</td>
<td>Dev</td>
</tr>
<tr>
<td>VTOL</td>
<td>Elevate Aerospace Alpha 2</td>
<td>Vijayawada, India</td>
<td>2</td>
<td>65</td>
<td>131</td>
<td>Dev</td>
</tr>
<tr>
<td>VTOL</td>
<td>EVA X30</td>
<td>Toulouse, France</td>
<td>2</td>
<td>162</td>
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* Passenger seat count for narrow-body aircraft; total seat count otherwise.
* Range estimated with cruise speed and endurance.
* Concept cancelled project; Con: conceptual design; Demo: demonstration design; Dev: currently in development; Prod: currently in production.
* Intermediate designs between 328 and 328-LBM not shown.
Appendix II: Carbon price and GHG emissions covered by ETS schemes (Ramstein et al., 2018, p. 22)
Appendix III: Criteria tree for alternative aircraft propulsion selection

Appendix IV: Detailed results of the overall composite weight of each alternative