Aviation's future energy requirements

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Means of reducing environmental impact

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Abstract

The aviation sector is approaching a crossroad where the industry will have to decide on what path to take going forward in terms of its’ energy needs. One path continues with the usage of non-renewable fuel resources such as jet fuel with the clear potential that global emissions will continue to rise, whereas the other path leads to newer technologies such as sustainable aviation fuels, hydrogen, and battery powered electric aircraft.

Currently these new technologies are not widespread globally and the most mature out of the three is sustainable aviation fuels. However, the supply still falls short of the immense demand that exist. Hydrogen, and in particular battery powered aircraft, create a possibility to dramatically reduce, or eliminate all emissions created by the energy consumption from aircraft. Unfortunately, similar to sustainable aviation fuels, the supply is limited and inadequate considering what would be required in the future. Further, the hydrogen that is being produced today is usually created using non-renewable methods. This is expected to change in the future as renewable electricity will become more commonplace.

Motivation for the industry to change towards a more renewable and sustainable energy storage can be either through regulations, supply stability, and consumer demand. Several regulations, or guidelines are either enforced today, or will become in the future managing the amount of greenhouse gases are emitted. Emissions are then for example subject to taxation, and specified amounts of renewable energy sources must be used within certain time intervals. Consumer demand for more environmentally friendly travel is likely a large motivator as trends indicate that the general population is becoming more aware of the impact their travel pose on the global climate. To avoid being relegated to the side-line, aviation actors should be encouraged to engage in potentially drastic changes to more sustainable.

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1 INTRODUCTION

Globally the issue of an increasingly changing, and more volatile, climate have over the recent years attained more and more attention in various media outlets, governments, and the public. Evidence that the manmade introduction of different greenhouse gases, and pollutions have an impact on the behaviour of the environment (IPCC, 2021) are today generally accepted globally. As human population numbers are projected to increase, coupled with increased living standards for people in countries with historically lower emissions, the overall emission of greenhouse gases is expected to increase (Johnson S. K., 2018) and a common approach on how to solve the issues is needed. The international community have over the last decades tried to formulate a cohesive approach on how to mitigate the effects and causes of the increase in greenhouse gases through different agreements. For example, the Kyoto protocol in 1997 and the Paris agreement in 2016 (Council on Foreign Relations, 2021).

In a report from the Intergovernmental Panel on Climate Change released in 2014 it is concluded that 14% of the global greenhouse gas emissions are from the transportation sector (IPCC, 2021). These emissions include both commercial and leisure transportation from road, maritime, trains and aviation. When emissions are divided into subgroups, road traffic emit the vast majority with around 73% (Ritchie & Roser, 2021). Whereas the aviation sector emits around 12% which is similar to the maritime industry. The truck and automotive industry have over a couple of years seen an increasingly rapid eagerness to reduce the amount of greenhouse gas emissions produced by their products (Casper & Sundin, 2020). This most likely driven by new, disruptive, and innovative technologies being introduced to the market. A more conscientious consumer market who want to decrease their own personal sum of emissions. Or, through government incentives such as subsidies and taxation relief.

One change is the introduction of alternative energy storage, and propulsion technologies compared to the traditional internal combustion engine with gasoline (Börjesson, Lundgren, Seriina, & Nyström, 2013). Electric propulsion with energy storage in the form of advanced batteries have been widely adopted in certain parts of the world with companies, such as Tesla, being very prominent with their consumer cars. The change from conventional energy storage in trucks is also being accelerated by similar means through battery storage or by using hydrogen in different manners. With the increasing pace of change in the automotive industry, one could expect that a similar shift would occur in other fields, such as the aviation sector. However, aviation is seemingly less willing to change from the traditional energy storage method of using kerosene or jet fuel. The technology exists and is becoming more mature by further research and development from the automotive industry.

So why is the aviation sector less inclined to rapidly shift energy storage methods into something that is more environmentally friendly by reducing emissions? This could be seen as a potentially existential threat to the aviation industry due to shifting public opinion and awareness of environmental impacts associated with their consumer behaviour. If aviation is too slow to react, and fail to change into a more sustainable operation, an altered public perception or increased regulations may reduce the competitiveness and business opportunities available to aircraft operators globally.

1.1 PURPOSE

With the changing climate, and the increasing focus on becoming more sustainable, questions arise on how a given sector or industry can adapt to new technologies. In the case of this report, the industry in question is the aviation sector. The author of this report has, together with most people globally, accepted the fact that greenhouse gas emissions created through our collective current behaviour must be reduced to limit the effects of a changing climate. Further, being a member of the aviation sector in the form of flight crew member, the author has an interest that aviation will remain a viable mode of transport for goods and people in the future.

So how can the aviation industry adapt for the future in order to persist as an acceptable mean for transportation? The author believes that a global, rapid, and decisive effort by aircraft manufactures, airports, aircraft operators, regulatory bodies and supporting industries need to find solutions on how adverse emissions can be reduced or eliminated. One way to achieve this could be through the use of alternative energy compared to traditional kerosene used in virtually all commercial aviation today. The automotive industry has experienced a relativity swift change towards more environmentally sustainable operations through the introduction, and adaptation, of for example electric cars. This report will, among other things, explore if the aviation sector potentially can make a similar change.

In this report the author will examine and answer certain research questions under the broader topic of sustainable energy storage technologies as seen below.

- What type of energy storage methods exist today, and in the short to medium term that could potentially be suitable for use in aviation?
- Which types of drivers, or motivators, exist for the aviation sector to adopt newer and more sustainable technologies?
- Are there any barriers to quick and widespread adaptation of the new technology?

1.2 LIMITATIONS

This report is exclusively based on various source material attained from the author's university's digital library, through digital search engines, news journals, governmental agencies, and manufacturers reports. The report has not used any laboratory work, or surveys created by the author, instead a reliance on other's research have been used extensively to compile this final product. Certain information, especially those derived from various manufactures should be viewed critically as only limited fact checking is available, in particular for claims the manufactures have made about potential future capabilities etc.

1.3 METHOD

Most of the research in the report have been acquired from digital resources through an extensive literature study. Resources for the various topics have been chosen with care to represent a factual representation. The material selected have been published by numerous international organizations, governmental agencies, non-profit organizations, different actors in the sector such as aircraft and fuel providers, and numerous research reports.

In order to find applicable information a combination of search engines have been used, with the predominating method being to utilise the Lund University digital library, and access points to reports and articles. Secondly, commercial search engines such as Google, and public encyclopaedias, such as Wikipedia and Britannica, have been used as method to find more universal information, but also to review references listed in various articles and websites to review the source material directly. Whilst reading through articles and reports, some also utilising a literature review method, additional resources have been gathered by discovering and searching for their primary sources as well.

During preparation of this report the work have been structured to only focus on one area at a time after an initial large-scale information gathering. For example, only working on a specific section before moving on to the next. By only working on a specific section at a time, it has been possible to focus more on the subject matter, and to carefully evaluating the information at hand. Certain reports and articles that at a first general glance could have been useful were on a second inspection found to be excessively outside of the scope of this report, where instead a more general overview was envisioned. Therefor some of the original material collected was discarded from the pool of information available and additional sources and information was instead obtained.

An emphasis on ample consideration for any potential motives for the various article and report authors have been undertaken. This was necessary as it was sensed that some organisations and manufacturers who have published reports could have sought after a competitive, and financial advantage by encouraging their proposed solution to different issues. For example, manufactures claiming that their technology would be more beneficial compared to a competing novel technology. In this report the author has tried to extract only information that is probable, or verifiable through multiple sources, and devoid of overly promotional material from manufacturers and other organisations. A greater confidence has been given to the numerous governmental, and international agencies and their published reports. This as it has been assumed that the material is presented in a more untarnished way, and not necessarily tainted by other interest than to factually present their findings.

Beside direct search terms to find information about specific topics precisely, certain more open-ended phrases have been used to locate further resources about the various subjects to discover new pathways of additional research. A list of common search terms, not all-inclusive, is provided below.

Aircraft fuel, environmental change, environmental impact, emissions per sector, oil crisis, supply disruption, consumer demand for environmentally friendly transportation, emission regulations, jet fuel, oil production, fuel storage, cost of energy, biofuel, biofuel refining, sustainable fuel, hydrogen, hydrogen power, hydrogen colours, electric vehicles, electrical batteries, charging techniques, electrical transmission, etc.

2 CURRENT JET FUEL

To get a baseline from which this report can make comparisons to other energy storage methods the following section will explore the use of jet fuel derived from fossil fuel, in particular crude oil. Globally the use of jet fuel is adopted as the main source of energy to power larger commercial aircraft and have an extensive infrastructure created around it ranging from feedstock extraction, refining, transportation to storage etc. (Hemighaus, et al., 2007). Jet fuel have been used in aviation as a source of stored energy to provide aircraft engines with the chemical energy required to provide propulsion. The jet fuel is also used to power ancillary systems during aircraft operations to power system, allow for handling on the ground, and is an integral part of modern aircraft and engine designs.

2.1 USAGE IN THE AVIATION SECTOR

Contemporary aircraft carrying larger amounts of passengers and cargo, with few exceptions, exclusively use turbine engines that are powered using jet fuel stored on-board the aircraft. The working principle of a turbine engine are objectively simple but have evolved to be immensely powerful and carefully crafted. To gain useful work, the turbine engine operates through three stages, compression, combustion, and turbine stage.

During the compression stage air is being fed into the engine through an open intake and passes through a series of small rotating aerofoils, the number of series varies due to differing design criteria. The power required to rotate the aerofoils comes from the turbine stage at the end of the engine. As the air passes the aerofoils, the air pressure and temperature increase significantly to between 30 and 35 times the normal atmospheric pressure, and between 550°C to 625°C (Hemighaus, et al., 2007). Because the amount of air in each area have been increased through the compression the next stage, combustion, will be more efficient and the subsequent useful work will increase.

After the air have been compressed it enters the combustion stage where the air is being infused by continuous spray, or misting, of jet fuel that have passed through nozzles designed for the purpose. Since the air have reached high temperatures in the compression stage, the air and fuel mixture start to combust without the need of any permanent external ignition such as sparkplugs or similar (Landis, 1999). As the air and fuel mixture is being combusted, the high continuous high pressure emanating from the compressor stage forces the gas mixture through the next stage of the engine, the turbine stage.

The combusted air and fuel mixture is being used to power the ongoing operation of the engine by passing through the turbine stage of the engine. In this stage the mixture passes through multiple series of aerofoils named stators and rotors (Hemighaus, et al., 2007). The purpose of these is to alternatively accelerate and decelerate the gas mixture where the stator, through careful alignment, forces the gas mixture to accelerate before hitting the rotors. As the mixture travels around the rotors, they are being forced to rotate whilst transferring the energy from the gas. After the rotors have been passed, the mixture passes through another series of aerofoils and the process continue until the designed amount of energy have been extracted from the combusted gases. The energy transferred to the rotors are further transferred through a connecting shaft, called a spool, which is attached and powers the aerofoils in the compression stage (El-Sayed, 2016). Assuming a steady supply of air being compressed, and jet fuel being provided, the gas turbine engine could theoretically continue to operate indefinitely.

2.1.1 Propulsion

When a gas turbine engine is attached to an aircraft its’ primary role is usually to provide them with a mean of propelling itself through the air. Adaptations of the basic gas turbine exist and which type being fitter to the aircraft depend to a large extent on what the design criteria is. For contemporary fixed wing aircraft there are two main categories of engines, turbofan, and turboprop. Both share the fundamental operation of a gas turbine engine but differ on how they produce most of the thrust required for the aircraft.

A turbofan engine has a large diameter fan section constructed with numerous fan blades attached to a central rotating hub. The required energy for the fan rotation is derived from the energy being transferred in the turbine stage. With the large fan a small portion of the air is being used to increase the pressure inside of the compression stage further. But the larger portion of the air being accelerated through the fan blades is being used to create significant amounts of thrust (El-Sayed, 2016, pp. 445-478). The ratio between the air being used as thrust compared to being consumed in the gas turbine is called bypass ratio. Over the last decades the trend has been to design engines with increasingly large ratios to increase efficiency, reduce fuel consumption, and through that reduce polluting emissions (Singh, Ameyugo, & Noppel, 2012).

Turboprop engines are powered by the turbine stage in the gas turbine engine whose spool is connected to a gearbox. A large propeller is connected to the gearbox which in turn create useful thrust for the aircraft. Compared to aircraft equipped with turbofan engines, a turboprop aircraft is more efficient when being operated at lower altitudes and speeds. If the aircraft were to fly higher and faster the efficiency start to decrease and the turbofan engine become more suitable (El-Sayed, 2016, pp. 532-538). Because of this, turboprop aircraft is often used for shorter regional routes where the difference in efficiency can be taken advantage resulting in lower fuel and operating costs.

2.1.2 Auxiliary usages

Many contemporary transport aircraft carry an auxiliary power unit (APU) attached to the aircraft. The purpose of the APU is to create high pressure air to start the aircraft engines, provide it with electrical power when external electrical power is unavailable or, when the engine generators are unavailable, for example before starting them or due to mechanical issues. Further, compressed air can be extracted from the APU and supplied to the aircraft air conditioner during the same situations as when main power generation is unavailable. The APU is a gas turbine engine variant called a turboshaft engine with a similar operating theory. A difference is that, when compared to the turbofan and turboprop engine, the turboshaft engine provides extremely limited usable thrust from its exhaust gases (El-Sayed, 2016, p. 553). Instead, almost all energy that have been converted through the consumption of jet fuel have been transferred into the turbine stage of the turboshaft engine powering generators etc.

2.2 MANUFACTURING

Contemporary conventional jet fuel is derived from crude oil resources. The resources are not readily available in all areas of the world and in many cases require transportation. This following section will explore the manufacturing process from the raw supply of oil to the final product ready for consumption.

2.2.1 Feedstock

To manufacture traditional jet fuel a suitable feedstock, or raw material, is required. The primary source is crude oil, sometimes referred to as petroleum, that in a liquid form is being sourced from wells extending far into the earth. Crude oil is a so-called fossil fuel which gains its’ name from the fact that it is the remanets of once living organisms. Animals and plant life alive millions of years ago have over time been covered by an increasing amount of sand, rock, and other materials. This excerpt significant and mounting pressure and temperatures on the remains and becomes during this process liquified (EIA, 2020). The liquid being created is composed of various hydrocarbon compounds with the primary three being paraffins, aromatics and naphthene (Cannon, 2017). Depending on the geographic location the extracted crude oil is sourced they can be of either high or low viscosity. Coupled with the varying viscosity follows a difference in colour that range from a light tan to an intense dark colour. Most importantly from a production point of view the crude oil vary in density where the higher viscosity crude oil is having a lower density compared to the darker lower viscosity counterpart. (Hemighaus, et al., 2007) The lighter crude oil is more desirable and valuable for oil product producers than the thicker crude oil. This is partly due to lower amount of sulphur and nitrogen within the liquid, and partly due to it being easier to further refine (Liu, Yan, & Chen, 2013). Even though the thicker crude oil is still less desirable for many applications, modern refining technologies allow for relative efficient extraction of the required final product.

Other sources include oil sands that are a type of sandstone that have been saturated with crude oil, these are mostly being exploited in Canada where the largest known deposit exist. Similar deposits exist in for example Venezuela (Liu, Yan, & Chen, 2013). These oil sands can be used as feedstock to refine the infused crude oil to other oil products. This feedstock requires additional treatment compared to ordinary crude oil and have a higher amount nitrogen, sulphur, and oxygen.

2.2.2 Global feedstock source locations

Crude oil is found in varying amounts in various types of climates. According to available documents the detected total global reserve of crude oil is just below 1700 thousand million barrels. To put that number in perspective one could make a comparison to the total number of barrels of crude oil consumed every day is around 99000 thousand (BP, 2018). The distribution of the crude oil is however not evenly balanced globally, and a significant majority of the known reserves, almost half of the worldwide reserves, are in the Middle East.

The global demand compared to the produced crude oil is skewed where certain parts of the world create an excess in relation to their consumption, whereas other regions consume more than they can produce. This supply and demand differential lead to large quantities of crude oil being transported from the place of production to the place of consumption. Oil producer statistics indicate that, for example Europe, a large consumer of crude oil, lacks direct access to the feedstock and must import it from other global regions. Compare that with the United States that over the last couple of years have increased their domestic crude oil production and import around three percent of its’ total consumption needs (EIA, 2020).

Lacking domestic feedstock resources can lead to dependency on the importation of, for example crude oil or refined products, which in turn can be used as a negotiation tactic globally (Kettell, 2014). Supplies might be limited, sanctioned, or have the price being inflated resulting in an acute deficiency of material and products in the affected region.

	Proved reserves[1]	**Percentage**
Middle East	807,7	48%
South & Central America	330,1	19%
North America	226,1	13%
Commonwealth of Independent States	144,9	9%
Africa	126,5	7%
Asia Pacific	48,0	3%
Europe	13,4	1%
Total	**1696,7**	**100%**

Figure 1: Amount of crude oil available for exploitation in different regions. (BP, 2018)

2.2.3 Oil extraction

The techniques to extract crude oil have been explored for centuries with the earliest documented wells being in China as early as the year 347. Techniques that are similar to present extraction methods dates to the 1850s with sites being developed in Azerbaijan, Poland, and North America (Totten, 2004). Processes involved to create an extraction site, from inception to termination, can be summarized in five different phases and are discussed in the sections below.

2.2.3.1 Planning

As discussed in 2.2.2 the location of crude oil is not equal across the globe, instead it dispersed over large areas where some are more suitable for crude oil than others. In order for an initiative to open a new source of crude oil to be successful skilled geologists are requested to survey areas of land and determine if it is suitable for future exploitation. It is possible to establish smaller wells compared to full-scale production wells. These can be used for continued appraisal and confirmation that crude oil is present in each location. (Netwas Group Oil, 2021) After a location have been deemed commercially viable in terms of crude oil availability, the geography and the properties of the material underground needing to be drilled through is examined. Using the results of the potentially varying materials a construction plan is created that outlines the specific locations of the well infrastructure, as well as how the well is to be drilled.

2.2.3.2 Drilling

When the planning phase have been completed, work on the site can begin. To access the crude oil underground a well is drilled with a hole diameter between twelve cm up to a meter. As the well is being created, metal casing or pipes are being inserted that may be further reinforced by cement between the well wall and the metal casing. The casing allows for better structural integrity compared to a construction without (Rigzone, 2021). The drilling process is accomplished by rotating a specialised drill bit connected to a rotating shaft called a drill string. As the well is drilled the length of the drill string is extended by installing additional sections to it. Excavation is provided by the drill bit either crumbling or shearing the sections of rock as the well is extended downwards (Netwas Group Oil, 2021). To cool the drill bit, and avoiding overheating, a drilling fluid is pumped under pressure through the drill string and out of the bit. The excess fluid collects the excavated solids, be it mud or rock, and transport it up to the surface where it is separated from the drilling fluid which is then

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[1] Expressed as thousand million barrels.

redirected back into the well. During the drilling process there is a risk of a so-called kick to occur, this happens when the pressure in the well is greater than the pressure from the drilling fluid. If corrective actions are not taken in time the well may blowout with a great amount of force that can lead to substantial environmental pollution. A noteworthy example in recent history being the American oil rig “Deepwater Horizon” that is estimated to have been the largest oil spill in U.S. history (Zeller Jr., 2010).

2.2.3.3 Completion

At the completion of the drilling for the production well a couple of steps needs to be taken prior to operations being. Depending on where the last metal casing is located, either in the crude oil reservoir or above it, different methods are used to allow the transportation of the oil. If the metal casing is in the reservoir, numerous holes are drilled into it for the oil to seep in. If the metal casing instead ends above the reservoir the end is fitted with a filter to avoid foreign debris to enter whilst also providing for better structural integrity (Rigzone, 2021). Common for both methods are that a separate pipe is lowered into the well that will transport the crude oil to the surface. This pipe is of a smaller dimension which create a potentially faster fluid extraction velocity. In addition, the pipe, in combination with the surrounding metal casing, reduce the risk of environmental pollution if one of them were to develop a leak.

In many cases the crude oil reservoirs have an inherent high pressure and by creating a path for the pressure to equalise, for example a pipe to the surface, a flow of oil should occur, and no additional mechanical systems are required. If the pressure in a specific reservoir is too low to create a natural flow of crude oil, a smaller pipe can be fitted (Cannon, 2017). Alternatively, the pressure inside of the reservoir can be increased artificially or mechanical lifting machines can be used.

2.2.3.4 Production

When the move into the production phases begins the well starts to produce crude oil that can be transported or stored in preparation for consumption. After the well have been completed it becomes self-sufficient (Rigzone, 2021). This is true if the pressure in the crude oil reservoir can be kept at a high level to maintain a good flow of oil through the piping. The pressure will however drop over time because of the withdrawal of crude oil. Depending on how much resources are remaining, in addition to how economically viable it would be, modifications to the well can be made to extract additional amount of crude oil (Cannon, 2017). Modifications range from servicing the existing piping, replacing the piping with smaller dimension tubing, increasing the pressure inside of the reservoir, or forcing crude oil through the insertion of other materials such as water that will displace the oil.

2.2.3.5 Closure

Even though numerous techniques exist to extract as much crude oil as possible from a well, even the most advanced and cost intensive methods still only extract around 75% of the total capacity. More rudimentary methods perform even worse and are usually only above to recover around 33%, significantly less than half of the total available crude oil in the reservoir (Cannon, 2017). As the price of crude oil is variable it may become uneconomical to continue to strive to extract more oil through more expensive methods and because of that oil wells are often closed or abandoned when their usefulness has decreased. The proper way of closing a well is accomplished by removing the surrounding infrastructure in and surrounding the well. After that, the drilled hole used to access the reservoir have to be sealed to avoid contamination to occur as well as removing polluted soil surrounding the well. This effort can become very costly. Because of this a significant number of wells are left in a mothballed state in the hope that the price of crude oil will rise in the future making it economically beneficial to start once again operating the well (Rigzone, 2021). In certain situations, the wells may become abandoned for various reasons such as bankruptcies or seizures at which point the public may have to take the economic burden to sanitise the area surrounding the well (Frosch & Gold, 2015).

2.2.4 Refining

Crude oil left in an unrefined state is not able to act as jet fuel, automotive gasoline etc. and requires extensive treatment in large oil refineries to yield useful final products. The refining processes can be expressed as three different stages starting with separation, upgrading, and conversion.

2.2.4.1 Separation

During the separation stage the crude oil is being distilled at the refinery. The purpose of the distillation is to take the homogenous crude oil and divide it into different categories for various future uses. This is the first and arguably most important step in the entire refining process and will process the vast amount of the raw crude oil entering the refinery. For the crude oil to begin to separate a significant amount of heat must be introduced, as high as 540°C (Hemighaus, et al., 2007). As the oil is being heated it starts to boil but will do so at varying temperatures. The gases that form during boiling can rise through a large vertical column. The gases that rise will, as they start to cool, become liquified again and are accumulated and collected at various levels within the column. When considering the liquid oil products that eventually becomes jet fuel, the boiling temperature range is between 205°C to 260°C and amount to around 10% of the total product yield of a given amount of crude oil (Planete Energies, 2015). The separation process alone is unable to extract all of the available end products and leaves a large amount of heavy oil unrefined. So, in order to fulfil product demand and maximise output of the feedstock the heavier oil requires extra processes that will be discussed below. If no further processing would occur, for example upgrading and conversion, the product after separation is called straight run (Hemighaus, et al., 2007).

2.2.4.2 Upgrading

After the various oil products have been extracted from the crude oil further refining is undertaken to remove or replace undesirable elements. Examples of these elements could be liquids with a corrosive property not suitable for engines or pungent smells. The origin of some of the elements are a sulphur construction named mercaptans and can in many cases be converted into so-called disulphides that do not share the same unwanted properties. To achieve this change, the total amount of sulphur in the oil product is often not altered. Instead, it is forced to change chemical form using different catalysts materials such as copper and sodium. Alternatively, the oil product can be subjected to hydro processing that introduce hydrogen and use that as a catalyst (U.S. Environmental Protection Agency, 2019). During this process molecules containing sulphur are broken into new compounds. The sulphur becomes hydrogen sulphide, and it is possible to remove from the product, reducing the total sulphur content, which could be of benefit for local air quality as the oil product is consumed.

2.2.4.3 Conversion

Using only straight run products would let a large amount of crude oil to waste, so to avoid that the heavy oil that remain after the initial separation stage can be converted to more usable products such as kerosine and diesel fuels. One method is to break apart the untreated hydrocarbons contained in the liquid. The process is called cracking and can subject the crude oil to intense heat (Hemighaus, et al., 2007), alternatively be exposed to catalytic materials.

2.3 INFRASTRUCTURE

Use of jet fuel to power larger modern aircraft is universal but require intricate production, processing, transportation, and storage practices. It is very seldom the case that an airport is in immediate proximity of an active oil reservoir and extraction well, in combination with a processing and storage area. Instead, various oil products are shipped from different areas to refine the crude oil to their respective final consumer.

2.3.1 Manufacturing and transportation

Energy demand from fossil fuel sources such as crude oil is extensive globally and on a more regional level such as the European Union. Being a large consumer of crude oil, the EU is unable to meet the demand with internal resources and thus must import it from other regions. Transportation of the crude oil to various refineries is made either through systems of dedicated pipelines that deliver the resources from the source. Alternatively, it will be shipped on large oceangoing ships to ports where it can be further distributed on freight trains etc. (Hemighaus, et al., 2007). Crude oil in an untreated state is not suitable for use as aviation fuel thus requires processing at large refineries. Focusing on the EU, 85 different refineries exist in the region and are together able to supply much of the jet fuel consumed only requiring a relatively small amount of importation (Nivard & Kreijkes, 2017). Like the transportation of crude oil, the refined jet fuel is transported by dedicated pipelines, ships, trains, and roadgoing trucks. The selection of what type of transportation system is used depend on local demand (Nivard & Kreijkes, 2017). A large demand might validate the use of a capital and infrastructure heavy deployment of a pipeline system, whereas a low demand might only require a truck.

2.3.2 Airport storage

Jet fuel storage methods at airport vary depending on their geographic location, security assessment, and building code. Two main storage methods can be seen globally and include large tanks of differing sizes being placed either aboveground or underground. The volume that the tanks can hold varies widely and is between 75 m^3 to 12500 m^3 and can be installed in larger clusters to increase storage capacity (Austerman, 1997). Aboveground storage tanks are usually larger than their underground counterparts. Both types of storage tanks can be made using welded steel as a shell and coated to resist leakage, monitored through dedicated equipment, and foreign contaminants. For underground storage tanks they can also be manufactured using fiberglass. In order to mitigate the risk of any contaminants being provided to the aircraft the storage tanks are equipped with an accessible sump system that should be able to remove water or other solids periodically (Hemighaus, et al., 2007). Further, the fuel being supplied to the aircraft is siphoned from the top portion of the jet fuel using a buoyant fuel boom.

2.3.3 Delivery to aircraft

Depending on the scale and operations on an airport its' fuel delivery system will differ but will generally be divided into three different types of distribution. These can either be a hydrant system, mobile fuel tanker or fixed dispenser location (Hemighaus, et al., 2007). On larger airports it is common to deliver jet fuel via a hydrant system where there exists a large common storage of fuel in or in proximity to the airport. The fuel is being fed through underground pipes to various locations, normally aircraft stands, around the airport grounds. Via access points certain specialised fuel trucks can extract the fuel from the underground pipes and have it pass though on-board filtering and metering equipment before being supplied to the aircraft under pressure (Austerman, 1997). For medium airport, with fewer refuelling events, not requiring the more intricate hydrant supply system mobile refuelling system can be used. The system utilises a truck that receive and store jet fuel in a large tank mounted to it. Similar to the hydrant system the truck has equipment that filter and measure the fuel on-board and delivered. Lastly, for small airports with few refuelling events a combined fixed storage and dispensing tank can be used but requires the aircraft to move to the station and can reduce aircraft turnaround efficiency (Hemighaus, et al., 2007) compared to the hydrant and mobile fuel tanker.

2.3.4 Aircraft storage

For larger aircraft three main different on-board and internal fuel storage methods exist such as rigid removable tanks, bladder tanks, and integral tanks (Aeronautics Guide, 2017). Rigid removable tanks are, as the name implies, possible to remove from the aircraft for maintenance, repairs, or replacement. They do not provide additional structural support for the aircraft but must be affixed to attachment points inside the aircraft to prevent movement. A common installation location is in the aircraft wings in order to not encroach on space inside of the aircraft cabin. The rigid removable tanks are constructed using various materials including metal, plastic, or fibreglass (Whitford, 2004). Bladder tanks are constructed using non-rigid and flexible material that similar to a rigid removable tank does not provide any additional structural support. A reason for selecting a bladder tank is that they can be installed in places where outside access is limited. Folded up the bladder tank can be inserted into the aircraft and unfolded once in place. Securing of the tank is required using various fastening devices as to remove the possibility for the tank to move during operation. If the bladder tank develops a leak this can be patched with relatively uncomplicated and inexpensive methods (Aeronautics Guide, 2017). Larger aircraft are designed as to maximise the amount of fuel available whilst adding the least amount of weight, this can be accomplished with integral fuel tanks. Removable rigid and bladder tanks are separate structures which adds weight, whereas the integral tank instead utilise already existing structures such as the aircraft wings. To avoid fuel from leaking from the wings they are treated with flexible sealant compounds. Since the integral fuel tanks are non-removable, maintenance and repairs are harder to accomplish, and extra safety precautions need to be adhered to (Aeronautics Guide, 2017).

2.4 ECONOMICS

Pricing of jet fuel is variable and is tightly connected to the price of its' feedstock, crude oil. If the cost of purchase of a barrel of crude oil increases, the cost of a barrel of refined jet fuel will increase at a similar rate. Examining the historical price of crude oil an assumption can be made that large variation will take place during, or in the immediate time before, a large global or regional event occurs (Kettell, 2014). Some noteworthy examples are the so-called oil crisis that occurred in 1973 where a regional conflict in the middle east caused embargoes on the exportation of crude oil and products to other nations supporting the nation of Israel.

The ensuing lack of supply compared to the demand caused a massive increase, almost 300%, in the price of crude oil, and thus also its’ refined fuel products.

An unusual situation occurred in the beginning of 2020 which led to a negative price of crude oil (Nawaz, 2020). This was as the large global pandemic of Covid-19 was surging internationally. This was the first time in history but can be explained by looking at supply and demand. As the world started to lockdown to minimise the impact and spread of the virus, significant amounts of crude oil were still being produced. This led to the market being oversaturated and quickly running out of storage space for the oil which caused the oil to become a liability for the oil producers.

The amount of fuel required to fly a given distance is the same regardless of the fuel costs and a given airline will have around 10% of its’ total yearly expenses tied to fuel. This means that an increase in the purchase price of jet fuel will mean that the airline need to increase ticket prices in the future to offset or, suffer a reduced earning. In order for airlines to guard against sudden increases in fuel price and gain more financial stability an option for hedging fuel exist (Morrell & Swan, 2006). Fuel hedging is when an airline agrees over a fixed fuel price with suppliers for a certain amount of fuel or, for a certain period of time. In the event of an increase of fuel prices above the agreed amount, the airline is not requried to cover that expense. But, in the event of a decrease in fuel price the airline is still contractually obligated to pay the higher fixed price.

2.5 ENVIRONMENTAL CONSIDERATIONS

Emissions that arise from the consumption of fossil fuels, example jet fuel, drive the warming of the atmosphere due to greenhouse gas emission. This is a worldwide phenomenon and include direct and indirect effects from the actual burning of the fuels to manufacturing and transportation. Internationally aviation is calculated to account for around 2.4% of the total carbon dioxide emissions with an approximate additional 2.6% from other gaseous releases and aircraft induced contrails. This brings the total warming contribution to around 5.0% globally (Overton, 2019).

Different regions have different amounts of emissions with the United States for example reporting an approximate 12% of their domestic transportation emissions coming from aviation and meaning 3% of their total greenhouse gas creation. Research indicates that unless new technology is widely adopted in the aviation sector, its’ associated global emissions will continue to increase substantially (Energimyndigheten, 2017) until 2050.

2.5.1 Carbon dioxide

As fossil fuels, in any form, are being consumed and burned it will create waste products or emissions. When an aircraft consumes jet fuel to provide it with thrust or ancillary services a significant portion of the emission takes the form of carbon dioxide, approximately 70% (Overton, 2019). As the carbon dioxide is emitted and released into the atmosphere it will create a heating effect that is long lasting since it takes an extended amount of time to be dispersed naturally. After a unit of carbon dioxide is released, it will be reduced by approximately 30% over the course of roughly 30 years. A further 50% will be removed from the atmosphere over the next couple of centuries, and for the last 20% to be absorbed naturally takes millennials (Lee, Lim, & Owen, 2013). The relationship between one kilogram of jet fuel consumed is not proportional to the amount of carbon dioxide being created. Instead, for every kilogram of jet fuel being burned, 3.16 kilograms of carbon dioxide is generated regardless of what phase of flight this occurred (Overton, 2019). Naturally if a reduction on carbon dioxide emissions is sought, the demand for jet fuel consumption must also be reduced through more fuel-efficient aircraft designs and engines.

2.5.2 Nitrogen and sulphur

When jet fuel is consumed it will, in addition to creating carbon dioxide, produce exhaust gases containing nitrogen and sulphur. The nitrogen gases act in both a warming, and cooling manner but will overall adversely act as a greenhouse gas. Nitrogen on its’ own adds to the heating of the atmosphere. But nitrogen also react with methane that is an even more powerful greenhouse gas and through a reaction effectively reduce the amount of methane that the nitrogen comes into contact with. This will have a potentially cooling effect, but the as stated before, the overall effect of nitrogen emissions are adverse (Overton, 2019). Sulphur when being found in aircraft exhaust gases will act as a cooling agent by reflecting parts of the sun’s energy back and out of the atmosphere. However, counterintuitively, if the sulphur is reduced or removed from the exhaust gases new chemical reactions will occur from the nitrogen and still create a small overall cooling reaction (Unger, 2011).

2.5.3 Contrails

A consequence of the burning of jet fuel is the formation of water vapours found in the aircraft engines exhaust gases. This is especially noticeable for onlookers when the aircraft is travelling through an area of high humidity and low temperatures since the water vapour is condensed and frozen into small particles that can linger for an extended amount of time. The water vapour creates a marginal warming effect, instead the main warming comes when aircraft are flying and creating contrails (Overton, 2019). The condensation can take place since the exhaust gases also include fine particulate matter that the water can adhere to and led to the creation of larger water formations.

When contrails are formed, they can remain airborne for a long time, spread over a large geographic area, and become so-called contrail-induced clouds which look like naturally forming high cirrus clouds. These clouds are remarkably effective at trapping infrared energy that is emitted from the earth and generate a warming effect that is three times more potent than the exhausted carbon dioxide (Fichter, Marquart, Sausen, & Lee, 2005). The contrails are usually dispersed in a relatively short time, a couple of hours, compared to at worst millennials for carbon dioxide but, considering the vast number of flights that are operated daily and globally, the effect becomes measurable.

2.5.5 Manufacturing and transportation

During preparation and production of a crude oil well, significant emissions are released from the reservoir, in particular fossil methane gas. Methane gas is a highly potent greenhouse gas that are around 80 times more effective at trapping heat than a comparable volume of carbon dioxide. Methane alone is estimated to cause at least 25% of the overall heating that occur in the atmosphere (Watts, 2020). Methane can be captured and stored to an extent for use as a flammable gas. Gases not captured must be dispersed as much as possible and is usually set alight in a controlled manner, this process is called flaring and create significant amounts of carbon dioxide (Gould, McGlade, & Schulz, 2020). When considering the refineries from an emission viewpoint one can determine that they continuously emit a combination of nitrogen oxides, carbon monoxide, hydrogen sulphide, and sulphur dioxide (Prioleau, 2003). Estimates indicate that the global petrochemical sector, here counting extraction, transportation, and refining is responsible for around 15% to 40% of the total greenhouse gases caused by burning their subsequent fuels such as diesel, kerosene, and gasoline (Masnadi, et al., 2018).

2.6 SUMMARY

Conventional jet fuel is currently the international standard energy storage medium for a vast majority of small, to large aircraft in commercial operations. The primary use for the fuel is to provide thrust via varying designs of gas turbine engines, and to power auxiliary on-board aircraft systems. These turbine engines have evolved significantly since their first use in the 20th century and are now highly efficient machines that have allowed for greater thrust whilst using less fuel, and in turn producing fewer emission as a result.

The feedstock used to create jet fuel is crude oil, a non-renewable material, which is extracted from underground reservoirs. Availability of crude oil is not equally distributed across the earth but is instead concentrated mainly to a few regions. Proved reserves of crude oil is mostly found in the middle east with close to half of the world’s total supply. To yield jet fuel the crude oil must undergo a refining process where it is being heated so that the different hydrocarbon combinations in the crude oil are forced to separate. After separation, further treatment is required prior to becoming a commercial grade product.

Crude oil and its’ associated final refined products are used globally, most of the infrastructure is therefore designed and tailored for these fossil fuels. The infrastructure include transportation through pipelines and fuel barrels, airport fuel storage, fuel delivery, and aircraft storage.

Prices for crude oil, and in extension jet fuel, can be volatile and this is especially noticeable when there is social unrest or global conflicts. Since the resources are pooled unevenly across the world, a reliance of stable transportation and fuel costs have evolved over time. Due to the significant scale of usage and production of jet fuel, the price per kilogram is relatively low when compared to other energy sources suitable for aviation use.

When jet fuel is being consumed it creates considerable amounts of carbon dioxide, nitrogen oxides, sulphur, and water vapor that together with particulate matter can develop contrails. All in all, these emissions are contributors to a warming factor of the atmosphere. The emission of carbon dioxide for example, need to be reduced dramatically to reach a carbon neutral growth in the future through new innovations.

3 SUSTAINABLE AVIATION FUEL

From a short-term perspective, a direct and immediate solution to reduce the amount of emission from the use of fossil fuels is the replacement of conventional jet fuel to sustainable aviation fuel, SAF. Jet fuel is recognised internationally as the standard for aviation energy storage and have extensive infrastructure in place to facilitate the extraction, refining, storage, transportation, and final delivery. It would be particularly challenging and costly to completely change the infrastructure within a short period of time. Use of sustainable aviation fuels would allow for the continued use of the already established infrastructure since it closely resembles the properties of conventional jet fuel with a few differences. Not being developed from fossil fuels, sustainable aviation fuels have a significantly lower emission profile by reducing the amount of carbon dioxide, sulphur, and particulate matter as it is consumed. However, one reason why the use of these fuels has not seen widespread implementation is the lack of full-scale production to meet demand coupled with a significantly higher price.

3.1 USAGE IN THE AVIATION SECTOR

Since sustainable aviation fuels are so similar to the jet fuel that is being used today no significant adaptation of the infrastructure or aircraft system are required assuming a mixing of sustainable aviation fuels and jet fuel prior to use. The subsequent fuel mixture is a so-called drop-in replacement for jet fuel where its’ primary use is to fuel gas turbine engines that produce usable thrust to the aircraft, or powers various aircraft systems, whilst generating fewer gas emissions, and reducing overall pollution created by the aircraft. By using an alternative to conventional fuels, the aviation industry would be in a position where continued global growth, estimated to be around 4% annually to 2038 (ICAO, 2020), could be achieved whilst dramatically reducing adverse greenhouse gases.

3.2 MANUFACTURING

The production of large quantities of sustainable aviation fuel differs from conventional jet fuel in that it does not require the extraction of fossil fuels such as crude oil. Instead, various biological feedstock must be sourced and refined utilising refining techniques where certain feedstock is better suited to certain refining methods.

3.2.1 Global feedstock source locations

Compared to crude oil, the feedstock for conventional jet fuel, that is found unevenly across the earth, feedstock used to create sustainable aviation fuel are more diverse and variable across the globe. For example, more frigid climates might have a large amount of forestry products available to refine into sustainable aviation fuels, tropical climates could have a larger proportion of agriculture crops or oil from palm trees (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021). One of the main benefits with the ambition to transition towards more sustainable resources are that it tries to avoid reallocating feedstock that could have been used as a food source directly, or reattribution of fertile land to produce energy crops (ATAG, 2017). Instead crops that can thrive in otherwise inhospitable environments or arid climates can be used which potentially increases overall land use and economic prosperity in otherwise infertile regions. Common for most regions are that there is potential in various waste products from municipal sewage to industrial residues (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021) that via certain refining processes can be converted into fuel.

3.2.2 Sustainable feedstock examples

Raw material that can be used to eventually become sustainable aviation fuels depends on what type of refining method is to be used, but also the geographic location and natural biodiversity. Four main categories of feedstock exist that fulfil sustainability criteria, but one must keep in mind that the feedstock must be sourced in a sustainable manner. Sugar and starch crops including sugar cane, sugar beet, corn, wheat, and rice (Sriroth & Piyachomkwan, 2013). Oil crops and subsequently recycled oil such as soybean, rapeseed, corn, sunflower, algae, and palm oil (Bauen, Howes, Bertuccioli, & Chudziak, 2009). Forestry by-products or crops grown specifically for energy extraction, examples being switchgrass, willow, and poplar (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021). And biodegradable waste from sewage, manure, and other residues (Bauen, Howes, Bertuccioli, & Chudziak, 2009). Below a couple of different feedstocks are listed that have been suggested (ATAG, 2017) to be especially good candidates for future sustainable aviation fuels.

3.2.2.1 Algae

Algae, also known as microalgae, are naturally forming living organisms that can thrive in vastly different environment. From small, sheltered ponds or lakes, to open oceans up with intense levels of salinity. The microalgae sustain themselves through an intake of different nutrients and exposure to sunlight, and can store carbon compounds, such as carbon dioxide (Leite, Abdelaziz, & Hallenbeck, 2013). Beginning in 2005 and a few years after that, massive capital investments were made into the developing field of growing algae with the expressed purpose to use it for fuel production. At the time it was touted as a superior feedstock compared to various plant-based solutions, this is partly due to an elevated amount of possible extractable oil, higher than 50% (Leite, Abdelaziz, & Hallenbeck, 2013), from the algae. Further, the algae can be cultivated in varying environments utilise underdeveloped arid landmasses and different water quality. But the initial hype quickly faded as it became apparent that the process of cultivating the algae, and subsequently extracting oil from it, was more difficult than expected (Lo, 2020). However, in recent years the interest in algae feedstock have risen again due to promising research and positive developments in various associated processes.

The methods in use currently for growing algae are either in the form of closed or open systems. Open systems are the cheaper option in terms of initial development and upkeep cost but is not as efficient as the closed system. Open systems are usually established as ponds or shallow basins exposed to the surrounding atmosphere. Water circulation can be achieved using rudimentary inexpensive tools to achieve aeration and mixing of the algae. Since it is open to the environment contamination of the cultivated algae is of concern (Leite, Abdelaziz, & Hallenbeck, 2013). Another concern is that the open system is vulnerable towards the inadvertent introduction of organisms that feed on the algae with the potential to exterminate the entire algae colony swiftly. Closed algae cultivation methods are more expensive to construct and operate but the yields are improved due to a more controlled environment. The systems range from transparent plastic bags, panels, to large vertical towers. As the systems are separated from external influence the potential for contamination of unwanted algae species, or predatory species, is dramatically reduced. Another positive aspect of the closed system is the ability to develop an algae cultivation site vertically which results in the method being more optimised for smaller development areas (Leite, Abdelaziz, & Hallenbeck, 2013). If placed indoors and away from natural sunlight, artificial light sources can be used. The use of artificial light has been a significant financial traditionally (Danila & Lucache, 2013), but the introduction of LEDs has decreased that effect to an extent. For both types of systems, the productivity and subsequent algae yields can be increased by introducing supplementary carbon dioxide (Leite, Abdelaziz, & Hallenbeck, 2013). The source of the carbon dioxide could for example be harvested from nearby emitters such as factories (Hartman, 2008), thus reducing the amount of expelled carbon dioxide into the atmosphere whilst boosting the algae’s development.

Harvesting the algae in preparation for oil extraction have proved to be difficult due to the fine granularity of the organisms, and the requirement to separate it from any excess water (Lo, 2020). The currently most common method of harvesting the algae is to subject the infused water to centrifugation to shed the significant percentage of the water. If the goal is to remove as much water as possible the amount of energy required becomes unsustainable though. If a compromise is acceptable, where a portion of the water can remain, the energy consumption can be reduced with around 80% (Leite, Abdelaziz, & Hallenbeck, 2013), but at the expense of reduced final algae yields. Another method is to let the algae and water pass through a filtration process, but if the specie of algae is not homogenous the filters quickly clog. A promising final method is to allow the algae to grow on a removable surface that is subjected to continuous water and nutrition. When the time to harvest arrives the waterflow can be interrupted, the removable surface extracted and the algae removed mechanically (Leite, Abdelaziz, & Hallenbeck, 2013). Studies suggest that this method is both simpler and yields more biomass than comparable methods.

3.2.2.2 Camelina

The camelina crop have a yearlong lifespan and quickly grows to around 60cm and develops small pods that contain a relatively high amount of lipid oil. Traditionally the oil has been used in cooking and to provide fuel for oil powered lamps (SLU Artdatabanken, 2019), but have recently garnered significant interest as a potential feedstock for sustainable aviation fuel. After the oil have been extracted the remains from the pods can be used, in controlled amounts, to feed animals (ATAG, 2017). Benefits from the growth of Camelina are that it thanks to its’ quick growth cycle can be harvested and then immediately replace with for example wheat in the same season, therefor increasing the overall yield a plot of land can produce. Further, the changing of crops reduces monocropping which can lead to environmental benefits (Garrity, 2020) through a reduction of fertiliser to compensate for lower yields. Harvesting of the camelina can be achieved using commonplace agriculture equipment such as combine harvesters. Studies suggest, (Stefanoni, et al., 2020), that the limited knowledge about the most efficient method to extract the maximum yield results in significant losses and unwanted foreign debris being harvested.

3.2.2.3 Cellulosic materials

Ethanol based fuels are today usually sourced from feedstock derived from various cellulosic materials. In an optimal system, the material required to create ethanol should not be taken from sources that could have been used for food consumption or similar as this could adversely affect food availability and prices (Denault, 2015). So instead, focus is placed on the waste products that are created during agriculture harvesting or food production. Another alternative would be to make use of plants that would otherwise not been utilised, or specific crops designed for energy consumption.

For the purpose of creating ethanol-based fuels, two separate categories of cellulosic materials could be defined. Firstly, one could use raw matter coming from different phases of food or forestry production. This includes for example the non-edible straw from sugarcane, wheat, corn, rice, and peels from potatoes or fruits etc. (Kumar, Tabatabaei, Karimi, & Horváth, 2016). From the forestry industry material examples include spillage from woodcutting, unwanted branches, or cut grass to name a few. Secondly, material and plants grown with the distinct purpose of being energy carriers and not for food consumption. These plants are usually selected on the merit that they should not require any large capital investment during their lifecycle and not require any significant upkeep. Most plants are multiyear and can regrow themselves after being harvested thanks to complex root systems. This has a benefit of also binding soils that otherwise could have eroded and increase the amount of mulch produced (Launder, 2002). Common plants used for this purpose are switchgrass, poplar, and willow.

3.2.2.4 Halophytes

One of the potentially adverse effects of emission of greenhouse gases, driving the rising warming of the climate, is the increased amount of soil salinity regionally. Certain regions in the world which currently have arable land could in the future become less fertile or even arid as salty water takes over making it difficult to grow various agriculture crops (Shrivastava & Kumar, 2015). Certain plants have evolved over time to be able to establish themself, or even thrive, in salinized soils. These plants commonly called Halophytes could be a solution for both food production, and a feedstock for sustainable aviation fuels. Currently only a small percentage of the global plant life can survive in salty conditions, roughly two percent (Yorke, 2020), and a fraction of that percentage have been domesticated for agriculture purposes. One species in particular, Salicornia Bigelovii, living in salty marshes could have future potential as a fuel feedstock. The seeds that it generates have a relatively high level of natural oils, around 30% (Glenn, Brown, & O'Leary, 1998), whilst almost leaving the remainder of the crop for food production. Another benefit from an increasing use of Halophytes is that they control coastal erosion which in turn could mitigate additional losses of arable soils from salinization.

3.2.2.5 Jatropha

The jatropha is in a family of around 175 species that generates fruits containing a relatively high amount of oil, 30-40% (ATAG, 2017), when extracted. Many of the species in the jatropha family is toxic for human and livestock consumption with some exceptions. The plant grows into a tree and attains a height of between 3 and 5 meters whilst remaining productive for up to 50 years (Feedipedia, 2016). One reason why the jatropha plant have garnered a lot of attention is the prospect of harvesting the extracted oil and grow the plant in less fertile soil than otherwise required for food production. The less fertile soil can for example be found in dry or somewhat stony terrain where water is scarce or infrequent. In the early 2000s there was a significant capital investment in developing countries where the prospect of growing jatropha plants were conveyed to offer a second and good income to local farmers (Feedipedia, 2016). However, the science surrounding the growth and subsequent extraction of the oil was not fully understood and estimates for the possible yield from jatrophas was exaggerated. Even though the plant itself can survive in dry conditions, it still requires a significant amount of water to generate a proper harvest. Estimates suggest that for every litre of oil produced, 20000 litres of water (Morrison, 2009) and yields will be roughly one quarter of some original estimates.

3.2.2.7 Municipal waste and recycled oils

Everyday products that are consumed daily create significant amount of waste materials. This could be packaging, paper products, and food waste. In the European Union, a lot of what is being discarded daily by consumers are being recycled, but a large portion is still left untreated and end up in large landfills (Essent Milieu, 2005). In the EU, an estimated 150 million tonnes of household and commercial waste are being created (ICCT, 2014) and suggestion exist that the amount will continue to grow, although recycling is expected to increase as well, reducing the amount of potential unused feedstock.

The process that would be used to convert municipal waste to usable fuels include a couple of steps. Firstly, the incoming waste need to be dried as it usually contains large quantities of water and other liquids not suitable for the upcoming processes. Drying can be accomplished using streams of air blowing through the waste. This encourages an aerobic conversion that emits heat which in turn act to dehumidify the waste, the result being a roughly 80% (Essent Milieu, 2005) dry compound. The dry compound can then be incinerated or used to create synthesis gases used in refining processes to create sustainable fuels. Emissions of greenhouse gases could according to some studies be reduced by almost 290% (ICCT, 2014, p. 6) compared to fossil fuels when the potential energy from municipal waste material is utilised instead of being discarded.

Another produced waste product is derived from various oils, either animal or plant based, that are being generated as a by-product during cooking. The European Union for example already has processes in place to repurpose the leftover oils to sustainable fuels. Estimates show that a little more than one million tonnes (ICCT, 2014) of waste oils are being recycled in the EU yearly as of 2013. Out of that million, roughly 70% is from a regional supply, whereas the rest is imported from other regions.

3.2.3 Refining processes

Depending on what type of feedstock that is available or planned to be used in the production of sustainable aviation fuel different refining methods exist. Below five different refining processes are detailed. Common for all are that they are currently approved for use in commercial aviation with varying degrees of blending to conventional fuels required prior to operational use. A larger number of processes exist in development (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021), but are not approved yet in accordance with the contemporary standards issued by the American Society for Testing and Materials, ASTM.

3.2.3.1 Hydro-processed Esters and Fatty Acids (HEFA)

The most used process to refine renewable feedstock resources to sustainable fuels is the HEFA method. Resources being used are various vegetable or animal oils, and the possible use of waste products from cooking oil. Oxygen is naturally present in vegetable oils and must be reduced or removed from the solution prior to the continued process (Jozsa, et al., 2019). The reduction of oxygen is enabled by subjecting the oil to hydrogen. The resulting fluid is then cracked and divided into various fuel sources, for example aviation fuel that is comparable with conventional jet fuel (van Dyk, et al., 2017). The HEFA fuel is then allowed to be mixed with jet fuel up to a maximum of 50% since the HEFA fuel lack certain aromatics found in regular kerosene (Wormslev & Broberg, 2019). Research have suggested that HEFA fuels could be processed and manufactured in contemporary oil refineries and therefor offer an already blended aviation fuel to consumers. However, the maximum concentration of HEFA to conventional fuels are currently limited to 5% (van Dyk, et al., 2017). But the maximum blend could potentially increase in the future and thereby reduce capital costs required to establish new manufacturing plants.

3.2.3.2 Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK(A))

Raw feedstock is extracted from biomass from, for example solid waste or dry plant matter, and the material is being heated to high temperatures while the amount of oxygen is carefully monitored and adjusted. The process creates a synthesis gas containing a desirable mixture of carbon monoxide and hydrogen (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021). However, undesirable elements such as tar and nitrogen are also created during the gasification and requires removal prior to undergoing the Fischer-Tropsch procedure to liquefy the synthesis gas. Different heating and gasification methods create varying amounts of undesirable elements requiring removal (Börjesson, Lundgren, Seriina, & Nyström, 2013, p. 11). The final product, FT-SPK, is like conventional jet fuel with a lower sulphur content but lack certain aromatics which means that it is only allowed in a mixed solution up to 50% (Wormslev & Broberg, 2019). Recent development has focused on adding certain aromatics to the produced kerosene which in theory would increase the amount of blending allowed. The main reason for the current maximum blend limit of 50% is a precaution that the lack of aromatics would degrade the sealing properties of the fuel system (ATAG, 2020). If the aromatics were to increase, as in the case of the improved FT-SPK/A, the seals could be proven to hold even with a higher blend ratio of sustainable aviation fuel (Radich, 2015).

3.2.3.4 Power to liquid (PtL) Fischer-Tropsch method

Globally the amount of renewable energy being generated from solar, and wind is steadily increasing (IEA, 2020). The increase in renewable energy, and the inability to exert exact control over the timing and amount of power created highlight a need to store or use the energy more efficiently. One way of harnessing the excess energy being created is to convert it into fuels that can be stored and used elsewhere. The process of converting electrical energy to fuel is called power to liquid and the resulting jet fuel product is approved to be blended up to 50% with conventional jet fuel (Schmidt & Weindorf, 2016). Electricity is utilised to drive an electrolysis process subjected to high temperatures, and when water is introduced, it is being converted into hydrogen. Separate to the electrolysis process carbon dioxide is being captured, either from the atmosphere or from industrial emissions, and converted to carbon monoxide. Hydrogen and carbon monoxide gases are then combined and processed using Fischer-Tropsch synthesis where they become liquefied forming a product similar to crude oil (Schmidt & Weindorf, 2016). The next step is to refine the oil in a conventional refinery and the resulting yield is around 55%.

3.2.3.5 Direct Sugars to Hydrocarbons (DSHC)

A company called Amyris have developed a method to create a renewable fuel that can be blended up to 10% (Wormslev & Broberg, 2019) into conventional jet fuel. The basis of the fuel is sugar derived from plants, such as sugar beet or cane, and being exposed to genetically engineered microorganisms where the yeast's genes are altered from creating ethanol to hydrocarbon. More specifically the hydrocarbons being created are called farnesane (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021). Currently there are no large-scale production as the material eventually creating farnesane is a very sought-after product in the chemical engineering sector (Jozsa, et al., 2019).

3.2.3.6 Alcohol to jet (AtJ)

Feedstock that contains starch or sugars can through a fermentation process be developed into an industrial alcohol solution, usually ethanol. The automotive transport sector can use the ethanol produced and mix it with gasoline to increase the sustainability of the fuel. However, the aviation sector does not currently have a similar approval but must instead refine the alcohol further to mimic the characteristics of jet fuel more closely (Jozsa, et al., 2019). Refining the ethanol involves dehydration to create ethylene that will subsequently pass-through reactors and catalysts where hydrogen is incorporated (Brooks, et al., 2016). The resulting product can then be extracted and separated into naphtha, gas, and jet fuel. Extracted jet fuel from the alcohol to jet refining method lack some of the aromatics that conventional aviation fuel has and thus must be blended. The approved blend is today 50%, an increase from the original approval of only 10% (Wormslev & Broberg, 2019) according to the latest revision of ASTM specifications.

3.3 INFRASTRUCTURE

The key advantage with using sustainable aviation fuels as a direct replacement to the contemporary jet fuel is the ability to perform the change with relative ease (ATAG, 2017). Chemically the two fuels are remarkably similar, and for good reason, as it has been tailored in a manner that allows for the already established infrastructure to be kept as it is today with only minor changes where required. This capability is called drop in fuel (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021), and could create a scenario where adaptation of sustainable aviation fuels are quickly becomes the standard fuel of the future due to the low associated costs due to absence of new aviation infrastructure.

3.3.1 Manufacturing and transportation

Some of the potential feedstock that are derived from the agricultural sector, for example camelina, can coexist within normal farming operations and equipment (Stefanoni, et al., 2020). However, the efficiency of the harvest and subsequent yields is suggested to be low with the knowledge and equipment in use today. Other crops such as jatropha and halophytes are still not widely adopted globally but studies estimate that introduction of the plants into the agricultural sector could be made rather cost effectively (Morrison, 2009). This could be especially beneficial when considering that both would optimally be used in less fertile lands than required for food production. Lastly, algae production is showing promise as a feedstock for future fuels but arguably require the most amount of capital investment compared to the other farmed crops. The extent of the investment can be altered depending on the required production efficiency sought (Hartman, 2008), but overall have the advantage that the growing sites can be placed on terrain and soil that is inhospitable to other types of agricultural production.

Similar to the feedstock from agricultural activities, waste matter from consumer goods and by-products from for example cooking, can be used as feedstock. For the waste material to be efficiently converted into usable feedstock it must first be processed via dehydration and filtration. Dehydration can be accomplished through an aerobic process (Essent Milieu, 2005) but currently no large scale plants for this purpose exist to handle the massive amount of waste that is being created and collected daily, globally and regionally (ICCT, 2014). Another process that needs attention is the requirement for the incoming waste material to be sorted, removing unwanted components that are not compatible with the upcoming processes. The sorting of materials can and is encouraged (Sopor, 2020), to be accomplished by the consumers themselves as the waste is created. But most of the waste that is being received by various municipals are not fully sorted (ICCT, 2014) and dedicated equipment can be used to varying degree of success to remove unwanted material.

The limiting factor currently is the quantity of sustainable aviation fuel available from the refineries. Refining the feedstock is currently a widespread issue on the merit that the facilities required do not exist or in far too few numbers (ATAG, 2017) when compared to conventional fuel production refineries. Depending on the type of feedstock being used, be agricultural waste or specific purpose grown crops, different refining techniques are used. This means that there is not one solution to how to most efficiently yield sustainable aviation fuels compared to oil refineries. But some refining techniques are estimated in studies to become more prevalent than others. By the year 2030 one assessment is that the HEFA refining method will account for almost half, 44% (Radich, 2015), of the overall production. The second most common method could be via the PtL method at an estimated share of 37% (Radich, 2015). Finally, the rest of the sustainable aviation fuels produced in 2030 would then be from AtJ, DSHC, and other Fischer-Tropsch methods producing the remaining 19%.

Examining the refineries currently in operation in Europe there are only five plants in total (Radich, 2015) and they are all using the HEFA method. A further two plants are being planned and will instead use Fischer-Tropsch method. If sustainable aviation fuels will become the de facto norm in aviation, ICAO estimates in a study that, to completely change the aviation from fossil fuels to sustainable aviation fuels, 170 large refineries (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021) need to be built every year from 2020 to 2050.

Since the fuels produced from sustainable feedstocks have been tailored, to be like conventional fuel types, contemporary transportation methods can be utilised. These methods include pipelines, large ships, and transportation over rail and roads. Some modifications might be required, especially replacing older O-rings and sealant, as the fuel produced from sustainable sources lack some of the chemical compounds, aromatics, compared to fuels derived from fossil fuels (Jozsa, et al., 2019). These compounds naturally have a sealing and lubricating properties and have been necessary to keep storage units from leaking. The removal of the chemical compounds could in some cases require new types of sealant materials able to keep their sealing property.

3.3.2 Airport and aircraft storage

Globally there are an estimated 41000 airports (Aeronewstv, 2015), and out of those around 18000 are commercial airports that regularly receive and handle passenger, freight, or business aircraft. Changing the entire fuel infrastructure on the airfields, and aircraft that serve it, would be a costly endeavour. For this reason, the sustainable aviation fuel is manufactured in a way so that it closely resembles the conventional fuel of today (ATAG, 2017). This allows for the continued use of current infrastructure and aircraft thus lowering the threshold of introduction of sustainable aviation fuels in the market.

There are however some differences in how the fuel is chemically structured that may need attention prior to increasing use of sustainable aviation fuels. Sustainable aviation fuels contain less aromatics than conventional jet fuel and therefore do not provide the same sealing properties. In older equipment and infrastructure, a risk exist that the tanks and lines could develop leaks as a side-effect. Newer infrastructure generally has better designed seals already from their inception and do not require any further modifications. Older equipment can however be retrofitted with updated seals so their time of usability can be extended (Jozsa, et al., 2019). As a stopgap measure a maximum allowable amount of sustainable aviation fuels are in place limiting the use to ensure that all seals in the current infrastructure will continue to function without any modifications (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021). These limits range from a blend of 50/50% jet fuel and sustainable aviation fuels to a blend of 95/5%. The amount allowed is currently based on approvals issued by the international organisation ASTM and varies depending on what type of feedstock and refining process was used to produce that fuel.

3.4 ECONOMICS

Purchasing sustainable aviation fuel today is significantly more expensive compared to conventional jet fuel. One reason why the price difference exist is because of the relative low amount of sustainable aviation fuels being produced, and the limited amount of fuel that is refined come from smaller developmental refinery plants that have yet to achieve economic of scale (ATAG, 2017). Currently there have been a modest actual uptake of these new fuels in everyday aviation operations globally, this could be argued to be because of the increased purchasing price making an airline’s potential profits lower than competitors as sustainable aviation fuels adaptation has been voluntary, not mandatory. If there is no demand for these fuels, then there is no motivation to expand the supply either through increased production. Reports suggest that, to encourage expanding fuel refining, that states and their government help to subsidize initial investment (ATAG, 2017). As supply increase, the theory is that the price of would decrease, in turn increasing demand. The profits, actual or future, could convince the major fuel providers that it makes financial sense to expand and diversify their portfolios with more sustainable aviation fuels.

Studies indicate that the average purchased unit of sustainable aviation fuels is today at least two times more expensive than conventional jet fuel. Depending on the feedstock and refining process used, the price difference can grow to a significant eight times that of jet fuel (Pavlenko, Searle, & Christensen, 2019). Currently the most inexpensive production route is through using the HEFA refining method with used cooking oil as a feedstock, this method is roughly twice as expensive as jet fuel. Utilising municipal waste material and the Fischer-Tropsch refining method the price multiplier is around four. Alcohol to jet’s multiplier is around five and DSHC approximately 10 (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021). However, focusing only on the actual price of the fuel can be misleading when future emission abatement cost is factored in. Sustainable aviation fuels are not free from emissions but reduce them significantly. For example, carbon dioxide abatement cost decrease with a decrease in emissions as illustrated here.

Assumed life-cycle CO2 reductions	**Illustrative CO2 abatement cost (€/tonne)[1]**
10%	€2170
25%	€870
50%	€435
75%	€290
100%	€220

Figure 2: Carbon dioxide abatement costs depending on GHG reduction
Adapted from “Destination 2050” (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021)

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[1] Expressed as thousand million barrels.
Calculated as (SAF price – Jet A1 price) / (carbon dioxide saving × Jet A1 emission factor).
Sustainable aviation fuels price 1176€/tonne, Jet A1 price 490€/tonne, Jet A1 emission factor = 3.16

3.5 ENVIRONMENTAL CONSIDERATIONS

Previously, the term for fuels derived from natural vegetable oils or waste products was biofuel, suggesting that the feedstock used was biologically friendly and could be used as an environmentally sensible alternative to fossil fuels. However, the feedstock to produce biofuel could in many cases also be used for food production, either for human or animal consumption. Given the scale of demand for fuels, there is a risk that food production would become sequestered with resulting shortages and price increases (Jozsa, et al., 2019). The term sustainable aviation fuel is used to explain a holistic approach towards a fuel solution. Sustainability, in the context of fuel production, take into consideration not only environmental concerns, but also social and economic issues (ATAG, 2017). For example, the farming of a certain crop for fuel production should not take precedence over the ability to produce food at a balanced price for the local population. Nor should any processes during the production of fuel create undue risks or other hazardous environmental issues.

3.5.1 Carbon dioxide

Aircraft using sustainable aviation fuels will still emit carbon dioxide as the fuel is burned similar to if it were to use conventional fossil fuel. But whilst it is producing carbon emission, according to some regulations it does not count as greenhouse gas emissions (Jozsa, et al., 2019). The key difference is how the emitted carbon dioxide eventually is recycled through the environment. Fossil fuel feedstock comes from sources that are not renewable where the carbon is stored undergrown in liquid or gas form. When it is later being used, that carbon is released into the atmosphere and raising the amount of, for example carbon dioxide, leading to an overall warming effect. Using sustainable aviation fuels derived from sustainable feedstock sources, for example plants, the emitted carbon dioxide released into the atmosphere is consumed by plants for nutrients. These plants are then used to produce more fuel and it becomes a more sustainable circle.

To get a better overview of the overall emission reduction, studies on the amount of greenhouse gases being produced during the fuel's lifecycle, from feedstock to consumption, have been completed. Estimates show that a total lifetime reduction of GHG varies from around 95% reduction compared to conventional jet fuel, to around 25% (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021). The large variation of total GHG reduction is due to the use of different types of feedstocks and refining methods being utilised during the fuel manufacturing. Overall, the Fischer-Tropsch processing method achieves the highest amount of GHG reduction, especially when using feedstock sources such as municipal and agricultural waste products. An important note is that the calculations covering the overall GHG reduction does not include the potential effects of landmass change (Jozsa, et al., 2019, p. 128). For example, that a forest is being razed to increase the amount of farmland required to grow crops used in fuel production.

3.5.2 Nitrogen and sulphur

The content of nitrogen in conventional jet fuel and sustainable aviation fuels are similar and therefore the emissions are not dramatically different. Some estimates show that the change in emissions of nitrogen oxides between jet fuel and sustainable aviation fuels is less than 10% (Hamilton, 2018). On the other hand, the sulphur content in sustainable aviation fuels is remarkably low when compared to conventional jet fuel. The amount of sulphur contained in jet fuel is around 0,3% of the total weight of the fuel and contrasted to sustainable aviation fuels the sulphur content is less than 0,003% (Hamilton, 2018). Such as drastic reduction in emission will enhance the overall air quality, especially in the close vicinity of airports (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021) where the emissions from multiple aircraft are concentrated.

Due to the long usable lifetime for aircraft, where an aircraft can be in service for decades, technological innovations can be delayed compared to other sectors. As an example, the emission of sulphur from aviation have risen since 1990 (EASA, 2021) whilst other sectors have seen a steady decline in emissions instead. A change to sustainable aviation fuels could quickly reduce the amount of sulphur being created whilst still retaining older aircraft currently in use.

3.5.3 Contrails

Together with the emissions of nitrogen and sulphur are a variety of particulate matter are exhausted from the aircraft engines as it burns conventional jet fuel. As discussed, the amount of sulphur emitted using sustainable aviation fuel is lower than jet fuel and the amount of other matter is also reduced (van der Sman, Peerlings, Kos, Lieshout, & Boonekamp, 2021). The reduction has a positive effect on limiting the significance of contrails that are being created as aircraft fly in cold and humid environments as the moisture have less material to bind to, thus decreasing the contrail formation. Further studies are being conducted, but initial theories suggest that an overall reduction in contrail formation, and associated warming atmosphere warming properties, between 40% to 10% (McKinsey & Company, 2020) could be achieved assuming that the fuel being consumed is a 100% mixture of sustainable aviation fuels. Smaller decreases could be accomplished using a blend of fuels whilst still being meaningful since studies approximate that contrails could be multitudes more potent (Wormslev & Broberg, 2019) as a warming agent compared to carbon dioxide.

3.6 SUMMARY

Use of sustainable aviation fuels are an attractive solution to lower the overall emissions from the aviation sector, whilst at the same time not being required to do any dramatic changes to the general infrastructure required to operate aircraft globally. Sustainable aviation fuels are a drop-in replacement, requiring only smaller modifications to existing systems such as sealants in fuel lines, and storage tanks. Being a direct replacement could mean that substantial capital investment is not immediately required to replace entire aircraft fleets, and infrastructure.

An advantage for sustainable aviation fuels is that the feedstock used to create the fuel is much more diverse than that of conventional jet fuel. The feedstock ranges from various plants, microorganisms, to waste products. This diversification also allows for increased localised resource allocation depending on climate etc. Certain crops that are being studied as potential feedstock candidates for fuel production can grow in arid climates, or on agricultural land that would otherwise not be able to produce any crops used as a food source. To be classified as sustainable, the raw material is not allowed to be yielded so to conflict with food production directly or indirectly affect food prices. Waste material as a feedstock is often plentiful across the world and solves the problem of what to effectively do with these waste products. Internationally it is common to collect and dispose of the waste in large landfills that can pollute the surrounding area. Depending on the original feedstock, different refining processes are used where the currently most common method is through a process called hydro-processed esters and fatty acids, HEFA. The subsequent fuel product can be mixed with conventional jet fuel up to a 50%/50% blend currently, but trials with higher amounts are currently being conducted. The need for varying inputs of feedstock, and associated refining processes create a potential issue where it can be difficult to reach higher levels of economics of scale like that of conventional jet fuel. Studies suggest that to move the aviation industry fully to only utilise sustainable aviation fuels, around 170 large scale refineries must be established annually until 2050.

The cost of sustainable aviation fuels is currently around twice as expensive to acquire for final consumers such as airlines compared to conventional jet fuel and is driven be an apparent lack of fuel being supplied. It is however expected that the prices will reduce in the future assuming a greater uptake and supply of the fuels. When also considering potential carbon dioxide abatement costs, a shift towards sustainable aviation fuels will incur a significantly lower cost when compared to a higher usage of conventional jet fuel. During the use of the sustainable aviation fuel various emission will still be present. Carbon dioxide as an example will still be present, but since the feedstock comes from renewable sources, the overall emission of carbon is expected to be neutral due to the carbon elements being absorbed into new plants etc. Nitrogen will still be emitted at similar levels to those of conventional jet fuel, but the amount of sulphur is predicted to be much lower, potentially increase the air quality around airports. Particulate matter is also expected to decrease in the emissions create by the consumption of sustainable aviation fuels, and this in turn will most likely reduce the number of contrails that are formed when matter and water vapour coalesce.

4 HYDROGEN

The potential of significant reductions in hazardous emissions produced by aircraft is one of the main motivators for an energy source shift towards hydrogen. When used, the amount of carbon dioxide is virtually reduced to zero compared to conventional jet fuel, or sustainable aviation fuels, and the main exhaust from the consumption is water vapour (McKinsey & Company, 2020). Hydrogen holds a lot of potential to positively change the environmental impacts from aviation but will require some technical innovations prior to becoming fully operational. Nevertheless, aircraft manufacture Airbus is currently researching hydrogen powered aircraft for its' feasibility (Airbus, 2021), and intend to bring the first generation to market by 2035.

4.1 USAGE IN THE AVIATION SECTOR

Three different types of hydrogen use have been envisioned by various reports and all have their advantages and disadvantages. Using the hydrogen as a fuel source for combustion in a modified turbine engine could be the next evolution of aircraft. Relying on turbine engines would mean that the aircraft could continue to be developed in a similar fashion (Thomson, Weichenhain, Sachdeva, & Kaufman, 2020) as it customary today with the biggest change arguably being how and where to store the hydrogen. Using fuel cell technology with hydrogen as fuel is another avenue to be explored. The electrical energy being created by the fuel cell could power several electrical motors and batteries. This could pave the way to more radical aircraft designs (Thomson, Weichenhain, Sachdeva, & Kaufman, 2020) that potentially are able to be more optimally designed for efficiency than conventional aircraft.

A hybrid approach would combine the two technologies, direct combustion, and the use of fuel cells would be used in tandem where the main propulsion is envisioned to be derived from the hydrogen combustion. Whereas the fuel cells and stored electricity could power auxiliary systems and provide power assistance when required (McKinsey & Company, 2020), for example during take-off and climb. The hydrogen could be used to power aircraft in either a compressed gaseous form, or in a liquid and extremely cold form. Studies suggest that the use of liquid hydrogen most likely would be in liquid form as it allows for twice the density compared to gaseous form (Baroutajia, Wilberforceb, Ramadanc, & Olabid, 2019).

4.1.1 Direct hydrogen combustion

Combustion of hydrogen inside of a gas turbine engine is expected to be an evolution of conventional aircraft in service today (McKinsey & Company, 2020) as much of the technology required is already available in different stages of maturity. Studies suggest that an increase in overall engine efficiency could be significantly higher in gas turbine engines powered by hydrogen compared to jet fuel, assuming that the hydrogen is stored at extremely low temperatures (McKinsey & Company, 2020). Further efficiency gains can be achieved due to hydrogen's high auto-ignition temperature (Airbus, 2020) allowing for a higher potential compression ratio inside of the gas turbine engine. A large motivation for use of hydrogen as fuel for combustion compared to conventional jet fuel, and sustainable aviation fuel, is the removal of produced emissions such as carbon dioxide, carbon monoxide, sulphurs, and particulate matter (Airbus, 2021). In the combustion cycle, nitrogen oxides are still created whilst using hydrogen, but is expected to be significantly less (Svensson, 2005, p. 101) compared with jet fuel.

Compared to sustainable aviation fuels, hydrogen as a fuel source is not possible to use as a direct replacement or drop in solution. Instead, substantial alterations must be undertaken to the engines, fuel delivery, and storage prior to introduction to service. Research acknowledge that it could be possible to retrofit aircraft already in active use, but that the recertification of the aircraft and its’ new systems would most likely be extensive (Thomson, Weichenhain, Sachdeva, & Kaufman, 2020). Therefore, a clean sheet design is probably more suitable similar to Airbus’ intention (Airbus, 2021) to bring new aircraft to market within two decades.

4.1.2 Hydrogen fuel cell

Removal of essentially all greenhouse gas emissions, except water vapour, can be achieved by using a fuel cell powered by hydrogen. In the fuel cell hydrogen can react with oxygen and electricity can be harnessed from the process. The electricity is then used to power electric motors, or to charge on-board batteries to be utilised a later stage. Electricity generation is inaudible and produces little to no vibrations. Comparing the use of fuel cells to using hydrogen in a combustion, the fuel cells do not produce any nitrogen oxides (Baroutajia, Wilberforceb, Ramadanc, & Olabid, 2019). However, the by-product of electrical generation is significant amounts of water vapour, up to nine kilograms per every one kilogram of hydrogen consumed (Thomson, Weichenhain, Sachdeva, & Kaufman, 2020). Two types of fuel cell technology exist as candidates for aviation purposes. Proton exchange membrane fuel cell (PEMFC) working at relatively low temperatures, and solid oxide fuel cell (SOFC) operating at high temperatures. Solid oxide fuel cells are heavier than a proton exchange membrane fuel cells but can operate with higher levels of hydrogen impurities (Baroutajia, Wilberforceb, Ramadanc, & Olabid, 2019). The most likely candidate of the two types of fuel cells for aviation use is currently the proton exchange membrane fuel cell (McKinsey & Company, 2020).

Hydrogen fuel cells are expected to require less overall fuel, 20% to 40% (Thomson, Weichenhain, Sachdeva, & Kaufman, 2020), for a given journey compared to hydrogen combustion, which together with the high efficiency gained from using electrical motors, will result in an overall higher efficiency of fuel cell powered aircraft than through combustion in gas turbine engines. Shifting the aviation industry towards hydrogen fuel cell technologies would most likely require radical new designs of aircraft. There is current research, and protypes flying, using retrofitted conventional aircraft using fuel cell technologies. One example being Zeroavia that have successfully flown a full-scale prototype (Zeroavia, 2021). One benefit of a completely new type of design philosophy could be the introduction and adaption of distributed propulsion, where numerous smaller electrical motors create propulsion compared to only a few as is customary today and use of boundary air layer ingestion. These new design elements have the potential to increase fuel efficiency by 20% to 30% (Thomson, Weichenhain, Sachdeva, & Kaufman, 2020).

4.1.3 Hybrid solution

Combinations of hydrogen combustion, fuel cell technologies, and electrical power storage in batteries can create various hybrid solutions for use in future aircraft. In 2020, aircraft manufacture Airbus announced their intentions of researching hydrogen powered aircraft that most likely would utilise hydrogen in both combustion inside a modified gas turbine, and via fuel cells to power it (Airbus, 2021). The purpose of a dual system, whilst increasing system complexity and total weight of the aircraft, is to achieve an overall higher efficiency. Envisioned aircraft from studies foresee the use of powerful gas turbine engines powered by hydrogen to work in tandem with integrated electrical motors during take-off and climb (McKinsey & Company, 2020) to suitable cruise levels. Upon reaching a sustained cruising position, the gas turbine engines would cease to operate, and the electrical motor will continue to propel the aircraft until a point where excess thrust would be required. At that point, the gas turbine would be reengaged.

4.2 MANUFACTURING

Different manufacturing methods exist to yield commercial yields of hydrogen. Some of these production techniques are very taxing on the environment, whilst others are dependent on renewable resources. In the following sections a more thorough examination of the various manufacturing methods is undertaken with their respective positive, and potentially negative attributes.

4.2.1 Hydrogen feedstock

Hydrogen is an extremely abundant element found virtually everywhere on earth, and in the wider universe. It has a great affinity to other elements and is usually found in organic materials, or in regular water (Jolly, 1999). Therefore, it is exceedingly rare to find hydrogen in its' natural form, and refining various materials, for example water, is required to extract hydrogen into usable quantities. After refining the hydrogen, it is stored as either a gas, or in liquid form. Interest in the use of hydrogen for aviation, and as an energy storage medium, is due to the high energy density, three times higher than conventional jet fuel when considering mass (McKinsey & Company, 2020). Further, the use of hydrogen as an energy source in future aircraft generate the possibility of reducing environmental impacts with a magnitude of three times that of synthetically created fuels (McKinsey & Company, 2020). The negative aspect is that the volume required for an equal amount of energy is significantly higher with hydrogen compared to jet fuel (Jolly, 1999).

4.2.2 Refining

Processes involved in extracting pure hydrogen are energy intensive, and while the subsequent usage of hydrogen in combustion or fuel cells are considered to drastically less polluting, the refining process could instead be a significant polluter (Toplensky, 2020). However, not all production methods are emitting hazardous greenhouse gases, and to differentiate between them a colour code system have been devised, where three among them usually are highlighted more than the others. These include grey, blue, and green hydrogen production methods and are further discussed below. The other colour grades are white, brown, pink, and yellow. White hydrogen can be yielded through extracting naturally occurring hydrogen that can be, but rarely, found in underground caves or reservoirs (Giovannini, 2020). There are no viable ways of effectively extracting the white hydrogen today. Brown hydrogen is generated by burning coal in a controlled manner where oxygen and water vapour is carefully monitored. During the process, the coal goes through gasification at around 700℃ which generates extractable hydrogen, but also carbon dioxide and monoxide (Giovannini, 2020). The process of gasification of coal to create hydrogen is the oldest known method and is exceedingly polluting assuming that the carbon dioxide is exhausted and not further used. Hydrogen is colour coded pink if it has been produced through electrolysis, and then only if the electricity used during the process have been sourced from nuclear power plants (Haynes, 2021). The last colour, yellow, is conflicted in the sense that some sources considers that the hydrogen produced must be sourced using electricity from solar energy, whereas other sources consider hydrogen produced by any locally available energy source which could be non-renewable as well (Dodgshun, 2020).

4.2.2.2 Grey

The most common method to yield hydrogen currently is through a process called steam methane reforming. Hydrogen created via this technique is categorised as grey hydrogen, and account for upwards of 95% of the total hydrogen production worldwide (Molloy & Baronett, 2019). The feedstock used to extract hydrogen is natural gases, and in particulate methane, that is heated to temperatures up to 1000°C. Whilst the gas is heated, water vapour is introduced under heightened pressure, and the combination of water and heated gases are exposed to a catalyst which allows for extraction of hydrogen, carbon monoxide, and dioxide (Brunel, 2021). During the process of creating the grey hydrogen, a substantial amount of hazardous greenhouse gases is emitted, and estimates suggest that the total emissions from the global hydrogen production using the above method is similar to those of the United Kingdom’s and Indonesia’s total emissions combined (Brunel, 2021).

4.2.2.3 Blue

Between grey and green hydrogen lies blue hydrogen. Blue hydrogen shares most grey hydrogen’s extraction methods, utilising steam methane reforming to yield hydrogen, and carbon monoxide and dioxide (Giovannini, 2020). The significant difference between the two are what becomes of the unwanted by-products such as carbon dioxide. Instead of being released into the atmosphere, the carbon dioxide is captured before being expelled, with current technology being able to capture around 90% of the carbon dioxide (Brunel, 2021) being produced during hydrogen production. The captured carbon dioxide is subsequently concentrated and transported via storage tanks, or systems of pipelines to designated sites used for long term storage. These storage sites are often naturally formed underground cavities, or disused oil and gas reservoirs (Brunel, 2021). Because the greenhouse gases produced in the hydrogen extraction process are not allowed into the atmosphere, the entire process is deemed carbon neutral, even though not all the exhaust gases are captured (Giovannini, 2020). Consideration is also made into the issue of what will become of the stored carbon dioxide in the future, with arguments being made that the process of long-term storage only delays the problem of increasing greenhouse gas emissions (Collins, Governments are being 'sold a pup on blue hydrogen from methane’, 2020), and not rectifying the underlying problems.

4.2.2.4 Green

The creation of energy using nothing, but renewable sources are becoming more common as wind, and solar electricity is being more widely adopted. Grey and blue hydrogen created through steam methane reforming create undesirable by-products such as carbon dioxide. Green hydrogen instead utilises an electrolysis process where electricity is used to extract hydrogen from regular water (Haynes, 2021), where the by-product is pure oxygen that can be used in various other applications. Assuming that the electricity is not created by non-renewable methods, the potential yield from green hydrogen could be completely clean (Giovannini, 2020), and free from hazardous greenhouse gases. Although currently significantly more expensive per kilogram to produce, there exist increasing interest in green hydrogen from regulators, for example from the EU, who see green hydrogen as a means of decarbonate many sectors (European Commission, 2020), and as a storage medium for renewable electricity.

However, currently there is not enough renewable energy readily available to transfer grey, or blue hydrogen production to green. But studies conducted within the European Union indicate that, given proper infrastructure investment, most regions could sustain a full shift towards renewal energy sources (European Commission, 2020). Private enterprises have also seen potential to reduce their greenhouse gas emissions and are swiftly, and increasingly moving towards more sustainable energy sources. A current example is the Swedish electricity supplier Vattenfall whom have entered a joint venture with large corporations in Hamburg, Germany. The joint venture aims at reducing the carbon dioxide emissions from 16, to 15 million tonnes per year (SvD, 2021).

4.3 INFRASTRUCTURE

Compared to sustainable aviation fuels, hydrogen in aviation is not a drop-in replacement for conventional jet fuel. This means that significant portions of the current infrastructure are either incompatible, for example fuel storage at the airport and aircraft, or simply not present at all or in inadequate supply as is the case with the amount of renewable electricity sources.

4.3.1 Manufacturing and transportation

Hydrogen, as discussed above, is ranked via different colour codes to indicate their source energy, but also how taxing the production is on the environment. Since the grey, and blue hydrogen still produces significant amounts of greenhouse gases, only green hydrogen and its' related infrastructure will be discussed as no hazardous emissions are created during the production.

4.3.1.1 Green hydrogen production plants

Beginning in 2020, a rapid and significant increase in interest, and announced intentions of creating more green hydrogen have been observed globally. During 2020, the planned global increase of green hydrogen production was forecasted to around 50GW of electrolysis capacity, this was later increased to just under 140GW intended electrolysis capacity within a few months' time leading into 2021, almost a three times multiplier (Collins, 2021). One of the largest current projects is being developed in the European Union, where 30 large energy producers are intending to create a large, interconnected network of solar power generation, tied to green hydrogen production. The estimated total electrolysis capacity would amass to around 67GW and would produce 3,6 million tonnes of hydrogen (Jackson, 2021). Studies suggest that the European Union in 2050 would require an electrolysis capacity around 500GW (Gandolfi, Patel, Vigna, Pombeiro, & Pidoux, 2020) to sustain a full shift towards hydrogen in select sectors. Utilising the full 500GW capacity would in theory be able to produce around 65 million tonnes of green hydrogen.

The European Commission have officially declared that it targets to make investments of around €400 billion to support the development and building of green hydrogen plants reaching a projected capacity of at least 40GW by 2030 within the European Union (European Commission, 2020) producing an estimated 5 million tonnes of green hydrogen (Gandolfi, Patel, Vigna, Pombeiro, & Pidoux, 2020).

4.3.1.2 Renewable energy sources

Green hydrogen is classified as environmentally friendly due to the material, and energy being used during its' creation are derived from renewable sources. In terms of the electricity used this include power harnessed from wind, solar, and hydroelectric plants. Power sourced from nuclear electrical plants are not considered green as it is not considered renewable or sustainable but are instead categorised in a separate colour code as pink hydrogen (Giovannini, 2020).

Statistics available from the public service Eurostat show that in 2019 the total electrical capacity created from wind power was 167GW, solar 120GW, and hydroelectric 150GW (Eurostat, 2021). All renewable energy sources combined accounted for around 34% of the total electricity being generated in the European Union (Eurostat, 2020). As the creation of green hydrogen is very energy intensive, one tonne of hydrogen requires around 52MWh of electricity (Gandolfi, Patel, Vigna, Pombeiro, & Pidoux, 2020), the current renewable energy capacity is not sufficient and requires further development. One study suggests that, to satisfy the requirement from the European Commission of having a 500GW electrolysis capacity by 2050, the amount of renewable electricity would have to be in the magnitude of around 1400GW. In order to meet the energy requirement, an estimated additional 35GW of renewable energy sources must be established every year from 2030 to 2050. (Gandolfi, Patel, Vigna, Pombeiro, & Pidoux, 2020) Keeping in mind that this capacity would be dedicated to the creation of green hydrogen, and to ensure future consumer electricity being generated from renewable source, even further investments in additional capacity is required to satisfy demand from other electrical consumers.

4.3.1.3 Transportation

After the hydrogen have been produced it must be transported to the final consumers, either small consumers such as individual businesses, or large industry complex. Currently, the most realistic, and cost-effective means of transportation is through an extensive network of pipelines (McKinsey & Company, 2020). These pipeline networks could be for a smaller regional area, or vast encompassing multiple countries or regions. On continental Europe a large network of pipelines already exists and is operational. The pipelines and are used to transport natural gas under high pressure to various consumers and regions.

Proposals to convert and repurpose these pipelines to hydrogen transportation are studied with the intention to create, a so-called, hydrogen backbone within the European Union. The expressed goal with the project is reuse up to 75% (Wang, Leun, Peters, & Buseman, 2020) of existing infrastructure by performing certain modifications to the network and extend it to new consumers via new pipelines. Prior to using the pipelines in their new role as hydrogen transporters they must undergo cleaning of any impurities that exist inside the pipes, lowering the allowable maximum pressure inside the pipes, or alternatively apply an internal sealant coating. The reason for the lower pressure or need for sealant coating is because the hydrogen can in certain circumstances react with the pipe walls. This reaction can lead to increased material brittleness and subsequent cracks forming, reducing the structural integrity of the pipelines (Gandolfi, Patel, Vigna, Pombeiro, & Pidoux, 2020). Hydrogen is expected to be transported under high pressure in a gaseous form through the pipelines with the pressurisation being achieved at designated compression stations. Liquification of the gaseous hydrogen for further use as a fuel source, for example in aviation, will most likely require facilities at, or close to the airport since it is deemed that the energy and efficiency losses incurred assuming transportation of cold liquid hydrogen would be excessive (McKinsey & Company, 2020).

4.3.3 Airport storage

It is assumed that potential future aircraft would be fuel by liquid hydrogen instead of hydrogen in a gaseous form. Liquid hydrogen is denser compared to when in a gas which also means that the energy density increases. For hydrogen to become liquefied it must be cooled to extremely low temperatures, as low as negative 253℃ (Jolly, 1999). If the temperature is allowed to increase, the liquid hydrogen starts to boil and becomes gaseous again. To minimise the boil off, carefully designed tanks are required that can maintain low temperatures for a prolonged period (Baroutajia, Wilberforceb, Ramadanc, & Olabid, 2019). This means that larger storage tanks currently used for keeping fuel supplies, such as conventional jet fuel, or sustainable aviation fuels are incompatible for use with liquid hydrogen (McKinsey & Company, 2020).

A method to circumnavigate the issue of storing the liquid hydrogen is to use the trucks that would deliver the liquid hydrogen to the airport as temporary storage. Or to repurpose old fuel tanks so they can store gaseous hydrogen under pressure, like the process of repurposing natural gas pipelines (Wang, Leun, Peters, & Buseman, 2020).

4.3.4 Delivery to aircraft

Airports commonly use two types of methods to refuel aircraft as they are parked on the ground during both long, and shorter stops. The main means of refuelling is either with an underground hydrant system, or through mobile fuel trucks delivering to different aircraft (Austerman, 1997). Larger airports more extensively use the underground hydrant method, whereas smaller airports often use fuel trucks due to their lower capital, and operating costs. It is expected that if hydrogen becomes more commonplace in the aviation sector, it is likely that the hydrogen will be provided in supercooled liquid form due to the increase energy density (Thomson, Weichenhain, Sachdeva, & Kaufman, 2020) compared to gaseous hydrogen.

A potential exist that the current airport hydrant systems are incompatible with liquid hydrogen as the low temperatures, and the chemical attributes of hydrogen, will make the underground lines brittle, and prone to cracking (Gandolfi, Patel, Vigna, Pombeiro, & Pidoux, 2020). One could imagine that reconditioning the hydrant lines would be possible, like the proposals to repurpose natural gas lines across Europe. But the requirement to deliver the hydrogen in supercooled liquid form will also risk increased boiloff as the lines are not necessarily designed to maintain the low temperatures required (Baroutajia, Wilberforceb, Ramadanc, & Olabid, 2019).

The issue of boiloff can be minimised if investment in dedicated fuel trucks is made that can handle liquid supercooled hydrogen and store it for a prolonged period with minimal energy losses (McKinsey & Company, 2020). Fuel trucks in use currently around internationally will be directly incompatible, but certain modifications to the equipment, and especially the storage tank itself, might allow for reuse of many components. At smaller airports with limited aircraft traffic, an increase in the fleet of fuel trucks may not be warranted. But at airports with more traffic an increase in the number of trucks might be required due to hydrogens greater volume per every kilogram (Jolly, 1999) compared to jet fuel and sustainable aviation fuels.

Refuelling of the aircraft is expected to take longer than what the industry have grown accustomed to due to the hydrogen's increased volume per kilogram. The amount of time required for an aircraft to fully refuel could be double (McKinsey & Company, 2020) that of an aircraft powered by conventional energy sources. Studies suggest that to allow for the aircraft to be utilised at similar levels as they are today, multiple refuelling hoses could be required. Alternatively wider gauges of hoses, or greater flow rates could be researched (McKinsey & Company, 2020).

4.3.5 Aircraft storage

One of the technical challenges that have been identified during previously undertaken feasibility research into hydrogen powered aircraft is the requirement of developing suitable storage tanks. These tanks should be lightweight as mass needs to be as little as possible in aircraft designs, durable, and well insulated to avoid hydrogen boiloff resulting in energy losses (Verstraete, Hendrick, Pilidis, & Ramsden, 2010). Hydrogen tanks have existed for a long time in the space industry to power rocket going into earth orbit and beyond, and to power spacecraft with electricity through fuel cells (Airbus, 2021). The technology is known and understood, but for effective adaptation in the aviation sector, certain refinements must be made. For example, an acceptable boiloff rate for certain space applications is around 1% to 2% of the total hydrogen stored per every hour. Whereas an acceptable level in aviation is expected to be around 0,1% of the stored hydrogen per hour (Verstraete, Hendrick, Pilidis, & Ramsden, 2010).

On conventional and contemporary aircraft, most of the fuel is stored in large tanks in the wings, and to a lesser extent in the aircraft belly. Due to the requirement to keep liquid hydrogen supercooled, and the larger volume occupied by hydrogen compared to jet fuel, storage in the wings is not suitable as the volume available is too little, and too hard to properly insulate (Baroutajia, Wilberforceb, Ramadanc, & Olabid, 2019). Instead, larger spherical or cylinder type storage tanks are required. Since the wings are not available for storage use, the hydrogen storage must instead be placed inside the fuselage, reducing the amount of space available for commercial application such as passenger, and cargo transportation. These hydrogen storage tanks can be manufactured to be relatively lightweight and may form an integral part of the overall aircraft structure, allowing for easier access for refuelling, maintenance, inspections, and insulation (Verstraete, Hendrick, Pilidis, & Ramsden, 2010). Some studies suggest that two types of tank designs can be used to store supercooled liquid hydrogen, where one of them are favoured due to lower weight. The first tank considered is of a multilayer insulation type, composed of various materials with good temperature control attributes. For the type to operate properly, a vacuum is required and is achieved using an outer wall. This double wall construction increases the overall weight of the tank but is highly efficient at reducing hydrogen boiloff (Verstraete, Hendrick, Pilidis, & Ramsden, 2010). The type of tank design only uses one wall, and instead rely on a special foam that is wrapped either around the tank or lining the inside of it. The final construction is larger than a comparable multilayer insulated tank, but of lower weight.

European aircraft manufacturer Airbus have officially launched research and development into future hydrogen powered aircraft with the project called ZEROe. Four concepts have been unveiled with three of them currently having their hydrogen storage tanks located inside of the fuselage. One concept however would utilise integrated power units called pods (Airbus, 2020), located inside of these pods will be the fuel cells, electrical motor, and liquid hydrogen storage tanks required to power the aircraft. This concept would not require any additional tanks to be placed inside the fuselage allowing for more commercial allocation for passengers and cargo.

4.4 ECONOMICS

Only considering actual fuel cost, hydrogen is significantly more expensive to purchase than conventional jet fuel but is expected to be cheaper than sustainable aviation fuels. Estimates for 2040 indicate that the per kilogram cost of liquid hydrogen could be between $2,60 to $3,50 for the final consumer on average (McKinsey & Company, 2020). This cost is still substantially higher than the estimated cost of $1,90 per kilogram of jet fuel in 2040.

Due to hydrogen not being a direct drop-in replacement to conventional jet fuel, the infrastructure surrounding the new aircraft becomes a factor. When considering the requirement for hydrogen production, electricity necessary, and transportation system the total investment cost for the European Union would be around $2,2 trillion by 2050 (Gandolfi, Patel, Vigna, Pombeiro, & Pidoux, 2020). Out of that total amount, €1,4 trillion would be allocated to increasing renewable electrical power sources such as wind and solar power. €0,4 trillion would be assigned to the electrolyser production sites that use the electricity to create green hydrogen. An equal amount of further funding of €0,4 trillion is to be used to construct power plants able to use stored hydrogen to create sufficient levels of electricity when the renewable sources are not operating to their full capacity. Finally, €0,1 trillion is earmarked to repurpose, and establish new transportation networks of pipelines across the European Union. In a Goldman Sachs report from 2020, they estimate that to mimic the Europe shift towards green hydrogen, the investment cost to 2050 for the United States would be $2,9 trillion, and the entire continent of Asia €4,4 trillion (Gandolfi, Patel, Vigna, Pombeiro, & Pidoux, 2020).

Comparing sustainable aviation fuels to liquid hydrogen, the hydrogen could benefit from a greater number of synergies, and subsequent cost saving through economics of scale. The hydrogen being produced is not specifically tailored to only the aviation industry, instead many other sectors could use the product. The potentially large market for hydrogen could spur significant investment and efficiency breakthrough (McKinsey & Company, 2020). Comparing this to sustainable aviation fuels, where the final product is more specific to the aviation sector only, and thus might not garner the same amount of investment to reach higher levels of scale economics.

4.5 ENVIRONMENTAL CONSIDERATIONS

Hydrogen could be a radical change in the way that individual final consumers, for example aviation, maritime, and power generation etc., emit various greenhouse gases or hazardous pollutions. Hydrogen by itself is devoid of any carbon and thus do not create carbon dioxide or monoxide as it is consumed. However, when producing the hydrogen, which is rarely found naturally, significant emissions could occur if the energy required does not come from renewable sources. In fact, only a small portion of the hydrogen today is manufactured using for example solar or wind power as renewable sources (Molloy & Baronett, 2019), and the production of hydrogen consequently is a substantial polluter. To reduce the emissions, so-called green hydrogen will have to be used.

The following sections are written with the assumption that the entire aviation sector have made a complete shift to green hydrogen to curb its’ emissions.

	Carbon dioxide	**Nitrogen oxides**	**Water vapor**	**Contrails**	**Total reduction**[1]
Hydrogen turbine	-100%	-50 to -80%	+150%	-30 to -50%	-30 to -50%
Hydrogen fuel cell	-100%	-100%	+150%	-60 to -80%	-75 to -90%

Figure 3: Comparison of climate impact from H2 propulsion compared to jet fuel. (McKinsey & Company, 2020, p. 21)

4.5.1 Carbon dioxide

Pure hydrogen does not contain any carbon and is therefore unable to create carbon dioxide as it is consumed (Baroutajia, Wilberforceb, Ramadanc, & Olabid, 2019). Currently two primary methods of using hydrogen are being developed, namely hydrogen combustion in a modified gas turbine engine to provide thrust, and fuel cell technology to create electricity which in turn is used to power electric motors (Thomson, Weichenhain, Sachdeva, & Kaufman, 2020). Assuming that the production of the hydrogen has been accomplished using only renewable electricity sources, no carbon dioxide emission will be created from the use of hydrogen leading to a complete reduction.

4.5.2 Nitrogen

Examining hydrogen as a fuel source in future gas turbine engines it is understood that nitrogen oxides will still be a factor to consider. Nitrogen oxides act as a greenhouse gas by creating ozone which in turn translates into an increasing temperature in the atmosphere, whilst at the same time reducing methane creating a cooling effect (Overton, 2019). The overall effect however is increased heating of the atmosphere. Use of hydrogen compared to conventional jet fuel, and sustainable aviation fuel, could drastically reduce the amount of the nitrogen oxides being released as emissions during combustion. One reason for the reduction is that hydrogen have a wider span of flammability. This allows the gas turbine engine to run at a leaner fuel mixture, whilst also running with a lower internal engine temperature (Svensson, 2005). Estimates indicate that a total nitrogen oxides reduction between 50% and 80% (McKinsey & Company, 2020) could be achieved if a shift from conventional fuel sources to hydrogen is accomplished when considering gas turbine engines.

When combustion occurs in a hydrogen powered gas turbine engine, nitrogen is created. To avoid that, and to achieve a practically emission-free energy source, the combustion cycle must be eliminated. Using a hydrogen fuel cell to create the aircraft’s electricity would allow for a complete elimination of nitrogen oxide emissions (Thomson, Weichenhain, Sachdeva, & Kaufman, 2020). As there is no combustion, only a chemical reaction inside of the fuel cell, no subsequent emission is produced except for water vapour (Baroutajia, Wilberforceb, Ramadanc, & Olabid, 2019).

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[1] Measured in carbon dioxide equivalent compared to full climate impact of kerosene-powered aviation.

4.5.4 Contrails

Hydrogen combustion in a gas turbine engine, or through electricity generation in a fuel cell will create a significant amount of water vapor. This can, given suitable atmospheric conditions, induce the formation of contrails. Estimates indicate that the amount of water vapor being emitted from the aircraft can be greater than a factor of 2,5 compared to conventional jet fuel (McKinsey & Company, 2020). The increased amount has the potential to adversely increase the contrails created which in turn create a warming effect on the atmosphere (Overton, 2019). However, fuel cells using hydrogen as fuel do not create any further emissions than water vapor, thus no particulate matter is emitted. Particulate matter is required for contrail formation as the water vapor need to coalesce onto something solid. Similarly, hydrogen powered gas turbine engines emit nitrogen oxides but little to no particulate matter. The removal of particulate matter in turn can be argued to reduce the overall formation of contrails (Thomson, Weichenhain, Sachdeva, & Kaufman, 2020). Further research suggest that potential future hydrogen powered aircraft should fly at cruise altitudes that are several thousands of meters below what is common with contemporary aircraft to further minimise their environmental impact (Svensson, Hasselrot, & Moldanova, 2004). Flying at lower altitudes will lessen the potential for contrail formation as the temperature normally increase closer to the earth’s surface.

4.6 SUMMARY

If the aviation industry were to pivot its’ fuel from conventional jet fuel, or sustainable aviation fuel, to hydrogen two separate means of using it is possible together with a hybrid version where both methods are utilised. The first method of using hydrogen is through combustion. This combustion can take place in modified gas turbine engines like those in active service currently. The power created in the engine would be able to rotate either a large fan, or propellers at high efficiency. The second method is to consume the hydrogen in on-board fuel cells which will create electricity. This electricity in turn can be used to power electrical engines, charge on-board batteries, and supply additional aircraft systems. Hydrogen can be stored in a gaseous state, either at atmospheric pressure or compressed, alternatively as a liquid at supercool temperatures. The most energy dense option is to store the hydrogen in liquid form, but it will be of a much greater volume compared to conventional jet fuel for an equal amount of energy. Greater required storage volumes means that fuel storage in the wings is not feasible, and instead a new and potentially radically new design philosophy is needed if hydrogen were to be introduced. These changes include chiefly how to manufacture, and where to position the large tanks required for these new aircraft.

Hydrogen is an exceedingly abundant element but is rarely found naturally in its’ pure form on earth, instead it needs to be yielded from other sources such as water. The refining of water to hydrogen is a highly energy intensive endeavour requiring. Currently the primary mean of hydrogen production creates a substantial quantity of emissions and is classified as grey hydrogen. Other colour codes for hydrogen exist where green hydrogen is produced by using electricity, solely from renewable energy source such as wind, and solar. Using renewable electricity sources means that the no hazardous emission is created during the production and consumption of green hydrogen.

The cost to purchase hydrogen is currently significantly more expensive when compared to jet fuel, but prices are estimated to reduce as production of green hydrogen is set to increase in the next couple of decades. Studies suggest that hydrogen at one point will be cheaper to purchase per kilogram than sustainable aviation fuels. However, substantial capital investment is highly likely required to renew entire aircraft fleets, airport infrastructure, hydrogen production sites, and to install additional renewable electricity sources globally.

In terms of the environmental impacts that will come because of a shift to hydrogen adaptation, the result is most likely going to be positive overall. As hydrogen is consumed no carbon emissions are created, nor any sulphur which will benefit the ambition to drastically reduce the release of carbon dioxide. If hydrogen is combusted in gas turbine engines nitrogen oxides are still expected to be emitted but at a lower volume compared to that of conventional jet fuel. The major emission from the use of hydrogen will be in the form of water vapor that can increase the quantity of contrails that develop when atmospheric conditions are susceptible to formation. Contrails are a contributor to an increasing atmosphere, but the formation can be managed by avoiding conditions where they most likely will form. For example, aircraft could be routed at lower altitudes where the temperature is higher, thus not suitable for contrail formation.

5 ELECTRIC BATTERY STORAGE

In contemporary aircraft designs the primary source of thrust is created by their engines consuming jet fuel derived from fossil feedstock. The engines do not have a sole purpose, but also serve other systems on-board the aircraft such as aircraft pressurisation, heating, and electricity generation. Out of the potential energy being created by the aircraft engines, roughly 95% is used as propulsive thrust, whereas the remaining 5% is used by these auxiliary systems (Thomson, Nazukin, Sachdeva, & Martinez, 2017). Over time the systems on-board the aircraft that use electricity have increased, thus reducing the dependence the fossil fuel being consumed. One example is the last generation of Boeing 787 aircraft that have been designed to be as efficient as possible. To that end the aircraft make use of electricity to power its’ hydraulic systems, cabin pressurisation, ice protection system, and main engine start systems (Hale, 2006). All of these have traditionally been power by extracting a portion of the power from the aircraft main engines, reducing overall efficiency.

Looking at the automotive industry where a rapid, almost exponential, electrification movement is underway (IEA, 2020), one could imagine that a similar shift could soon occur in the aviation sector as well. However, there are currently certain barriers that hinder a rapid change, the main reason being the storage capabilities of batteries which is currently not suitably efficient for aviation use. (Thomson, Nazukin, Sachdeva, & Martinez, 2017)

5.1 USAGE IN THE AVIATION SECTOR

One of the most significant expenditures of electricity in a fully electric aircraft would be to provide it with propulsive thrust. To create thrust from the on-board electricity, engines are used with associated propellers or fans. These engines are either powered by alternating current or direct current (Thomasnet, 2021), both having advantages as well as disadvantages compared with each other. Beyond providing thrust the on-board electricity would be used to power required auxiliary aircraft equipment such as the flight controls, pressurization etc.

5.1.1 AC Engine

Engines using alternating current as their main source of power consist of relatively few moving parts and are either categorised as an induction or synchronous motor. Both categories contain a static and a moving part called stator and rotor, respectively. Movement of the rotor, which can be connected to other systems to harness the rotational force created, is achieved through electricity being passed through windings of copper wire placed around the stator (Thomasnet, 2021). As electricity is moving via the windings, they create a rotating magnetic field that the rotor reacts to. The rotor in turn creates an electromagnetic field that create a torque movement and the engine starts to spin.

An induction AC engine is highly efficient but suffers some degradation due to friction, heat generation, and to a phenomenon called slip. This occurs as the rotor is never able to spin at the same rate as the theoretical maximum rotation created by the stator and its’ rotating magnetic field. An overall efficiency between 85% to 95% (Hanejko, 2020) is said to be achievable. AC engines have few moving parts and thus require minor maintenance (Thomasnet, 2021) and are expected to have a long service life. Many common home appliances or industrial equipment use AC engines since the input electricity taken from an average power outlet is alternating current (Hosch, 2006). This also eliminates the need to convert the alternating current to DC via a rectifier unit. However, most batteries supply direct current (Johnson S. , 2017) and therefor need to be converted into alternating current via an inverter unit. This inverter unit can increase complexity and introduce efficiency losses.

5.1.2 DC Engine

Like an AC engine, a direct current engine uses a stator and a rotor to convert electricity to rotational force. Smaller and simple DC engines have traditionally been constructed with magnets attached to the stator and an electrical conduit attached to the rotor. These engines can be around 30% (Thomasnet, 2021) more efficient than some AC engines. As electricity can flow through the conduit an electromagnetic force is created making the rotor spin. To facilitate the delivery of electricity to the rotor conduit a set of carbon brushes establish contact to a rotating commutator. This continuous rotation will over time consume the carbon due to the mechanical friction reducing the overall efficiency, and eventually requires maintenance or part replacements (Thomasnet, 2021). Contemporary DC engines are more frequently of a brushless type thus eliminating friction, maintenance requirements, and other adverse effects (Slemon, 2018). The operation of the brushless engines differs in the placement of the magnets which are placed to be part of the rotor. Rotational force is created through timed delivery of electricity to windings of copper wires alternately pushing and pulling on the rotor magnets. DC engines are generally able to provide high amounts of torque over a large range of speeds whilst being smaller than comparable AC engines.

5.1.3 Auxiliary systems

There is an increasingly swift move towards powering more of the aircraft systems with electricity than older and contemporary aircraft (Thomson, Nazukin, Sachdeva, & Martinez, 2017). These systems have been powered indirectly or directly by extracted energy derived from the running engines powered by fossil jet fuel. Examples include the pressurisation and climate control where bleed air from the engine have been used, various and numerous hydraulic systems that have relied primarily on engine driven pumps to achieve suitable pressures, and ice protection from diverted warm air from the engines (Thomson, Nazukin, Sachdeva, & Martinez, 2017). Removing the jet engine from the equation in a fully electrical aircraft requires new replacement systems to be developed and certified, as well as increasing the capacity of the electricity storage medium to provide adequate levels of power to all airborne systems. Reducing hydraulic lines and bleed ducts will reduce weight and complexity of an aircraft. But consideration must made as well to the increased amount of electrical cable (Thomson, et al., 2018) required to power an increasing number of systems.

5.2 BATTERY MANUFACTURING AND FEEDSTOCK

Contemporary batteries have developed to be immensely powerful and at the same time decreased in both size, and weight since their inception. The increased energy density is accomplished through the mix of select rare minerals that require complicated pathways to source and refine, and improved manufacturing process of the actual batteries. Materials used commonly today in batteries providing electricity to consumer products are often scarce and demand is expected to outpace supply within the decade (CNBC, 2021). The scarcity most likely will lead to it becoming more economically viable to recycle more batteries and their associated materials to satisfy demand, whilst also provide a more sustainable battery manufacturing process (Dahllöf & Emilsson, 2019). Because of material rarity, and sustainability concerns, new battery technologies are explored with more common source materials such as sodium that can be found in relative abundance (Charboneau, 2021).

5.2.1 Notable battery materials

Various materials have certain properties such as energy density, availability, ease of extraction, and cost etc. Combined in specific mixtures the materials can create some of the popular batteries that are used globally today. In the following paragraphs some examples of the more commonly used materials will be explored.

5.2.1.1 Cadmium

The use of cadmium in batteries are widespread as an important anode ingredient to work together with for example a nickel cathode. Regarded as a rare element it is usually sourced as a by-product from zinc or lead extraction. As zinc or lead is being heat treated fumes are created, in these fumes the small amount of cadmium, 0,1% to 0,3% (Britannica, 2020), are coalesced into larger proportions. Further treatment can increase the final cadmium product to be around 99% pure. Cadmium is toxic for plants and animals and tend to increase in concentration in various environments as it is not consumed naturally by living organisms (GreenFacts, 2015) with concentrations increasing higher up in the food chain. Too high concentrations can lead to potentially fatal liver and kidney damage in animals and humans.

5.2.1.2 Cobalt

Cobalt increases the service life of batteries as well as energy density due to its' properties of stabilising the various layered structures inside of the battery between materials (Patel, Lithium-ion batteries go cobalt free, 2020). Widely distributed across the globe, cobalt is usually found in small amounts, and greater concentrations for commercial purposes are typically located in comparably small local areas. The material is not commercially extractable directly, but are instead refined from by-products during mining and refining of iron, nickel, copper, zinc etc. Like nickel extraction the raw material is grounded into finer particulate matter and passed through a flotation process where a concentration of around 15% of cobalt (Taylor & Young, 2020) can be achieved directly. Further processing is required to increase the concentration. Studies suggest the mining and subsequent extraction of cobalt is an energy intensive and causes notable amounts of greenhouse gas emissions (Farjana, Huda, & Mahmud, 2019). Beyond that there are links to the dust and pollution causing birth defects and lasting breathing issues in the workers and inhabitants living close to mines (Mucha, Frankel, & Sadof, 2018).

5.2.1.3 Graphite

Dark grey or black in appearance, graphite is a carbon-based mineral that forms complex internal hexagonal structures and have seen increasing use in battery manufacturing since the 1970s (Britannica, 2021). Further applications for graphite include being a lubricant, pencil ingredient, and part of electric engines. The mineral is mined in either open pits or using underground excavation. The ore being extracted is not commercially viable due to low graphite concentration. This can be increased by multiple cycles of crushing the ore and isolate the graphite through a floatation process (Britannica, 2021) until a commercial grade is achieved. The mining process is known to be polluting the local environment surrounding the mines. Water sources can become so polluted that they become unsafe for consumption or use, and the fine particulate matter created from graphite extraction and processing causes respiratory issues for animals and humans (Whoriskey, 2016).

5.2.1.5 Lead

The initial use of lead in batteries was in 1859 and remains in use to this day. Lead is a heavy metal that is very dense, and soft thus easy to shape and cut. Material is sourced from underground mines or from recycled material containing lead. Ore recovered from mining are contain a low overall percentage, between 3% to 8%, of actual lead (Tikkanen, 2020). To increase the concentration the ore is grinded and filtered through a floating process separating the lead. After the subsequent yield is allowed to dry the concentration can reach between 50% to 60%. Lead is toxic to animals and plants and may cause birth defects, damage to the brain and nervous system (EPA, 2020), and left untreated fatal complications (Tikkanen, 2020).

5.2.1.6 Lithium

Batteries should be as light as possible, whilst at the same time be able to store significant amounts of energy. Lithium is the lightest solid material in the periodic table, has the greatest electrochemical potential, and have a notable energy density (Battery University, 2021). Lithium is found infused in natural salts, some types of ores, and brine solutions globally but where certain areas have a higher concentration than others. For example, the so-called Lithium triangle is located in South America encompassing Chile, Bolivia, and Argentina and together have the vast majority, 75% (Dye, 2021), of the global lithium reserve. The process of extracting lithium from brine involves the need to first access it, the brine can in some cases be in large reservoirs underground. The brine is left to dehydrate via evaporation in big water basins for up to 18 months. Using evaporation is an easy and effective method to extract lithium but requires the use of extensive amounts of water (Katwala, 2018) leading to irrigation issues for regional farmers. Products used in the production of lithium risk contaminating waterways (Dye, 2021) leading to health and environmental problems.

5.2.1.7 Manganese

Found around the globe in varying concentrations, manganese is the twelfth most abundant element but does not exist in a free form. Instead, the material is extracted from other ores such as pyrolusite (Britannica, 2020). An estimated 80% of the known resources of manganese is in South Africa that together with Australia produce around 40% of the world’s supply. Extraction is achieved by subjecting the mined ore to acids that acts as a solvent. The unwanted matter is separated, and the manganese can be filter out reaching around 90% (Britannica, 2020) yields. If concentrations of manganese in water supplies becomes too large, especially surrounding extraction and processing plants, it can lead to adverse health effects. The most notable is the risk of intellectual impairment in children or young adults (Bouchard, et al., 2011). The cost per weight is low compared with nickel and especially cobalt where manganese cost $0,8 per pound, nickel $7,08, and cobalt $34,98 (Moore Stephens, 2018).

5.2.1.8 Natrium or Sodium

The silvery metal is counted as the sixth most abundant material on Earth but does rarely exist in its’ metal form, instead being diffused into water or as salt crystals. Sodium is the common English name for the material but is also known as natrium from the Latin description. The solid metal type of sodium is used certain applications but is still produced at relatively low volumes (Britannica, 2019). Current extraction processes require the use of an electrolysis of sodium chloride, also known as regular salt. The finished sodium metal is very unstable and oxidises rapidly when in contact with air. To avoid oxidation transportation and storage must utilise various inert gases, alternatively lower the metal into specialized oils (Britannica, 2019). The metal is currently not widespread in battery applications due to its’ lower energy density and new technology. However, compared to other materials the environmental impact from feedstock sourcing is lower (Patel, 2021) than for example cobalt or lithium in part to the increased and ease of accessibility of sodium.

5.2.1.9 Nickel

In certain battery types of nickel is used as it delivers a high amount of potential energy storage with advantageous energy density for a relatively low cost (Nickel Institute, 2021). Two different types of ores are primarily sought-after during nickel extraction, and both employ different techniques to mine the metal. If the ore is in the form of sulphides underground mining is used, and if it is instead laterite ore open pits or topsoil extraction is utilised (Wise & Taylor, 2013). Extraction of the nickel infused in the ore is similarly different depending on the original ore. Sulphide based ore is grinded into fine particulate matter and the nickel is yielded by careful floating and magnetic extraction.

Following the extraction, the nickel particulate matter can be smelted and further treated. The process results in emission and pollution from sulphur and require significant energy. Laterite ores do not contain sulphides and thus do no create sulphur pollution during extraction. However, the process is energy intensive as the raw material need to be dehydrated from naturally occurring water. After dehydration further processing and smelting can occur at temperature ranging from 1300℃ to 1600℃ (Wise & Taylor, 2013). The mining and subsequent is reported to be quite taxing on the local environment surrounding the production (Opray, 2017) with gaseous emissions from the ores, greenhouse gas emissions from furnace burning, and slag material.

5.2.2 Battery types

Different types of batteries exist ranging from older technology to advanced combinations of materials. All of these have differing properties that make them more suitable in certain applications such as starting engines and the use in personal electronics. For electrical cars, the most common category is lithium-ion batteries which in turn come in various variants. Similarly, for fully electric aircraft a possible battery candidate would be Li-ion batteries. However, the energy density is currently considered to be too low for larger aircraft to be fully electric. Studies suggest that 500Wh/kg (Thomson, et al., 2018) is the energy density required before it becomes feasible to shift towards fully electric vehicles with similar capabilities as contemporary aircraft.

5.2.2.1 Lead Acid

The use of batteries using a combination of lead and acid to power various equipment was initially started in 1859 with the invention of the first rechargeable battery. Compared with newer types of batteries, the lead acid battery has a low energy density making them heavy and not suitable for everyday portable use (Battery University, 2021). Energy density is between 30 and 50Wh/kg and the battery cells have a normal voltage of around 2,1 volts (Epec, 2021). The clear advantage, and a reason why it is still in use today, is that the battery can provide a significant amount of current over a short time (Batteriföreningen, 2019). This surge current is used for example whilst starting large and small petrol engines. Another advantage is that the batteries are of relatively low cost to produce and purchase. One disadvantage with the lead acid battery is that it does not cope well with full discharge and recharge cycles as the material inside the battery quickly degrades during the process (Battery University, 2021). Further, the lead acid battery is not suitable or capable for fast charging, a charge lasting between 8 and 16 hours (Battery University, 2021), and thus not a good candidate in applications where fast charging is required. The battery instead is best used for small and short extractions of power, such as starting a petrol engine. Toxicity is a concern due to the materials being used (Batteriföreningen, 2019), lead and acids, and proper waste management is required to avoid environmental pollution.

5.2.2.2 Li-ion

Lithium-ion batteries, and its’ numerous different variants, are currently very widespread globally being a primary mean of energy storage for personal electronic devices etc. Normal voltage for a cell is between 3,3 and 3,7 volts (Batteriföreningen, 2021) making them incompatible as a direct replacement for NiCD and NiMH batteries. Li-ion batteries have a high degree of energy density, but it varies depending on what types of materials are used in the battery. Li-ion batteries can charge quickly given that the charging equipment can provide the required electricity. Fast charging can theoretically reduce the charging of the batteries to roughly 70% under one hour (Battery University, 2021).

One of the first commercially available Li-ion batteries in the 1990s is manufactured using lithium and cobalt. The combination goes under the acronym LCO and have an energy density of 190Wh/kg (Epec, 2021). Although having a high energy density, the LCO battery is not suitable for applications requiring sustained high power and is sensitive to proper charging and temperatures. If longer sustained power drain is required from the batteries, then a combination of lithium and manganese, LMO, might be more suitable. Exchanging the cobalt with manganese also reduce the purchase price as manganese is more widely available (Batteriföreningen, 2021). The useful life of the battery on the other hand is less than LCO batteries and likewise the energy density of around 135Wh/kg (Epec, 2021).

In contemporary electric vehicles common battery types include Li-ion variants constructed from nickel, lithium, manganese, cobalt, and aluminium. These are called NMC for the lithium-nickel-manganese-cobalt variant and NCA for the lithium-nickel-cobalt-aluminium variant. Both variants share a high energy density of 205Wh/kg for NMC batteries and 220 Wh/kg for NCA batteries (Ding, Cano, Yu, Lu, & Chen, 2019). Further, both batteries have a long lifecycle, but NCA batteries are a little bit more unstable in high temperatures (Batteriföreningen, 2021) than NMCs.

5.2.2.3 NiCd

Nickel cadmium batteries, NiCd, is a battery type that can be used with various applications either individually or packed together to form a larger cell. Each battery cell has a normal voltage of 1,2 volts (Batteriföreningen, 2019). Notable application for the battery is portable electronics such as older media players, toys, or other lighting equipment (Batteriföreningen, 2019). Nickel cadmium batteries are rechargeable by supplying electricity to it. Advantages for the battery include an energy density of roughly 30Wh/kg (Epec, 2021), the ability to go through cycles of discharge and recharges for a significant number of times, the ability of very rapid charging reaching 70% charge in minutes (Battery University, 2021), and good operating performance at low temperatures.

Even though the battery can go through many cycles, it is still subjected to the so-called memory effect where batteries over time lose some of its’ capacity. In NiCd batteries however the effect is temporary and can be overcome by ensuring that the battery goes through a full discharge and recharge cycle. Since cadmium is a material ingredient in the battery, a significant hazard and disadvantage for the use of the battery is its’ toxicity. Proper handling and waste management is required to mitigate the risk of polluting the environment. Due to that, the battery type is prohibited to use (Batteriföreningen, 2019) in the European Union and other countries, except for some specialised applications such as medical equipment, emergency services, and military use.

5.2.2.4 NiMH

Nickel metal hybrid batteries, NiMH, are similar to NiCd batteries but have the clear advantage in that it does not contain any heavy toxic materials (Batteriföreningen, 2019). Like NiCd batteries, the nominal voltage for any given cell is 1,2 volts which makes it a good option to replace older, often prohibited, nickel cadmium batteries. When the NiMH battery was originally introduced it was outperformed by many measurements compared to the batteries it was supposed to replace. However, after continued development, the energy density of the batteries has increased to around 100Wh/kg (Epec, 2021) and performs well in both high and low temperatures (Batteriföreningen, 2019), and are considered to be suitable for application where a high level of energy drain is expected (Batteriföreningen, 2019). NiMH batteries are capable of rapid charging cycles (Beck, 2020), making them a candidate for application where fast reenergization is required. Compared to batteries based on lithium, the NiMH batteries are not considered to be dangerous goods on-board aircraft which alleviates it from restrictions of use (Batteriföreningen, 2019).

5.2.2.5 Sodium-ion

Batteries based on sodium, and not necessarily requiring materials arguably less sustainable, have received growing attention as the use of electric vehicles are increasing globally (Charboneau, 2021). Sodium is widely available and is relatively cheap to purchase compared to other materials. But the technology is not yet so mature to be commercially viable for consumer products such as portable electronic devices due to a comparability lower energy density of 75 to 150Wh/kg (Durmus, et al., 2020) compared with above 200Wh/kg available from Li-ion batteries. Safety is increased with the use of sodium-based batteries compared to other types of batteries owing to the use of more stable materials that do not cause explosions or hazardous gases when damaged compared to Li-ion types (Charboneau, 2021).

5.2.3 Global feedstock source locations

The material used in the manufacturing process to produce Li-ion batteries involve multiple different materials that are not readily available equally across the globe. Instead, natural deposits of the various material are often found in larger reserves that are either found in a regional area or within the borders of individual countries. Lithium is found in great quantities in Chile for example, a country that is regarded as a stable, increasingly democratic, and sustainable after the previously ruling regime feel in 1990 (Carmagnani, 2021). Cobalt on the other hand often sourced from the Democratic Republic of Congo, DR Congo, which produce over 50% of the available cobalt internationally. The DR Congo have suffered at times from political instability, corruption, and ranks low on the human development index (Payanzo, 2021). The index measures among others life expectancy, education levels, and per capita income. Cobalt extraction in the DR Congo have been accused of using child labour (Katwala, 2018) that often perform the work without proper protective equipment. This and similar situations for other materials commonly used in the Li-ion battery production have resulted in increasing arguments that used batteries should be recycled more often, or alternative battery solutions should be sought (Katwala, 2018).

The availability of some of the material used in the production of Li-ion batteries are forecasted to decrease in the future as demand is expected to continue to rise, leading to shortages and increases in material purchasing cost. Already in 2022, a diverging trend is projected for copper where demand will outpace the supply (CNBC, 2021) that will slowly aggravate over time. The same is expected to happen with cobalt from 2025.

Nickel on the other hand is expected to have its’ demand outpace availability in 2024 and the production of nickel is not forecasted to increase significantly (CNBC, 2021) during the evaluated period. The sharp increase in demand for nickel is supported by an increasing amount of nickel being used in contemporary Li-ion batteries due to their relatively high energy density and associated low cost (Nickel Institute, 2021).

5.3 INFRASTRUCTURE

The progression from conventional jet fuel derived from fossil fuels, or from sustainable sources will require modification in the infrastructure surrounding airports and aircraft. Extensive pipelines networks, storage tanks etc. would not be required anymore, but an increase in electrical conduits for battery charging is necessary. Further, it is possible that the connections to the larger collective electrical grid must be strengthened and expanded (Bigoni, et al., 2018) to meet the significant rise in demand for electrical energy.

5.3.1 Battery manufacturing

An assumption can be made that fully electric aircraft become more commonplace, the batteries that store their energy will be similar to those already manufactured in significant numbers for the automotive industry. This will either lead to a shortage of supply and increase in associated cost, or the rapid development of further battery factories. The production of batteries has already grown substantially because of the growth of electric vehicles. For example, in 2017 around 30 gigawatt of battery storage capacity was manufactured globally (Eddy, Pfeiffer, & Staaij, 2019), that was a 60% increase from 2016 and studies suggest that a similar growth could continue. Today most of the batteries used in for example Europe is imported primarily from large manufacturing plants in Asia, but there are plans to increase regional production in Europe in the future.

5.3.2 Electricity generation

In the European Union roughly 2750 TWh of electricity is produced annually, and out of that amount around 43% is created using so-called conventional thermal (Eurostat, 2020) generation i.e., the burning of various fuel that are often from fossil non sustainable sources. The percentage of conventional thermal varies between different countries and depends to a certain extent on what type of natural resources the country has. Taking Norway and Albania as two examples, over 90% (Eurostat, 2020) of their total electricity generation is derived from harnessing water as an energy source in hydroelectric generation plants. Two further examples are the Netherlands and Poland that create over 80% of their total electricity from conventional thermal. The use of electrical aircraft often has the expressed purpose to reduce the greenhouse gases emitted (Heart Aerospace, 2021), but a true reduction or even elimination of greenhouse gas emission would be possible first when the electricity consumed are derived from sustainable sources.

5.3.3 Electricity transportation

Electricity is generated at power station, either from conventional thermal, nuclear, or hydroelectric etc. and requires a mean to be transported to the consumer. Today’s most common method of transporting electricity is through alternating current, AC, and large conductive metal wires. In the process some efficiency losses can be expected through resistance and heat (James & Granath, 2020) but can be alleviated by increasing the voltage to multiple thousands of volts. The increase in voltage is achieved in a transformer before the electricity is directed into wires that are either suspended in the air between large poles or buried undergrown. Use of suspended wires are commonplace assuming they traverse less populated areas due to their relatively high efficiency (Afework, Hanania, Stenhouse, & Donev, 2020).

Certain largescale consumers, such as heavy industry, may draw electricity straight from these wires as they can handle the high voltage. But most consumers require voltages that are significantly lower than those provided in the suspended wires. Therefore, the voltage is reduced in a second transformer located close to the final consumer. The voltage can be further reduced before consumption, for example an ordinary household requires between 120 volts and 240 volts (U.S. Department of Energy, 2003) to power appliances and other everyday electrical equipment.

Airports could be significant consumers of electricity. However, studies suggest that the electrical infrastructure could be required to undergo a process of upgrading (Bigoni, et al., 2018), assuming fully electric aircraft becomes more common. The grid reinforcement would emanate from the necessity to right-size the electrical conduits that would be used to deliver high voltage electricity to places where aircraft or their batteries were to be charged.

5.3.4 Airports and electric aircraft charging

Unlike sustainable aviation fuel, a fully electric aircraft will not constitute a so-called drop-in replacement where much of the airport infrastructure already built can be reused with minor modifications. Instead, electric aircraft will likely require new infrastructure to be installed at airport that wish to serve them. Further, the process of reenergise the aircraft will be an issue that have to be solved. This could either be through charging whilst on the ground in a turnaround, or by having a larger pool of spare and swappable batteries that can charge separately whilst the aircraft is continuing to operate.

5.3.4.1 On stand charging

Similar to how contemporary cars are being charged to refill their energy supply, one method to recharge the batteries would be to connect the aircraft to the electrical grid during ground stops. Already existing electrical connections to power aircraft systems whilst on the ground can provide approximately 90kVA (Bigoni, et al., 2018) equal to about 72 kW. Electric car chargers range from those used at home to high performance chargers found at service stations or other dedicated sites. The charge capability for home use ranges from 3 kW to 22kW, whilst high performance chargers can reach up to 350kW (Disdale, 2021). Assuming an electric car with a battery capacity of 100kWh, like high-end Teslas, charging at a 250kW station will take around one hour to reach full capacity (Hoffman, 2020). Available data from electrical aircraft manufacturer Eviation and their prototype small regional aircraft[1] Alice indicate that the on-board batteries are expected to have a capacity of around 820kWh (Eviation, 2021). Assuming that a high-end charger was to be used for recharging the aircraft, it is possible that that it would take several hours to fully recharge the batteries, making it incompatible with current turnaround times for aircraft. Other possibilities to shorten the time to recharge could for example be to use even higher capacity chargers (WSDOT, 2020), or use multiple chargers responsible for separate sections of the batteries.

5.3.4.2 Swappable batteries

With current technology it can be perceived that charging the electric aircraft whilst on the ground and during a turnaround is unachievable. An alternate approach to solve the issue of allowing the aircraft to have its’ energy replenished is to use exchange the batteries that have been used and insert new ones into the aircraft. If the battery swap were to be used, it is estimated that the change could take place within 15 minutes (WSDOT, 2020), thus remaining inside the window allowed in most contemporary turnaround slots. Since the batteries are removed from the aircraft, the available time to recharge them is increased, it would be possible to reduce the strain on the batteries as they are charged rapidly (Bigoni, et al., 2018). Instead of subjecting them to several hundreds of kW’s a more tempered approach can be explored that also will reduce the burden on the electrical grid. A benefit from charging the

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[1] Estimated range 440 NM with 9 pax + 2 crew or 2500 lbs cargo + 2 crew.

batteries more slowly is that it would be possible to schedule the charge to occur at times where electrical prices are lower, for example in the middle of the night. However, for the swap to be possible, multiple battery packs must be made available by the operator or by multiple operators working together.

Two potentially negative aspects (WSDOT, 2020) that come from the use of battery swapping is the need for more intricate mechanical systems to hold and retain the batteries whilst on the aircraft. This can increase the need for maintenance action and introduce new failure modes such as poor electrical connections between the batteries and aircraft. Further, for the battery swapping to viable, the infrastructure must be the same, or compatible with each other. For example, it would not be possible to use the technique if one country uses one type of batteries whilst another country uses yet another battery technology. This problem is likely to be overcome as the industry have historically been quick to adopt various technologies universally, an example being the use of standardised cargo containers called ULDs.

5.4 ECONOMICS

Historically the most significant cost in an electric vehicle have been the batteries that stores the energy required for propulsion. In large parts due to the increasing demand and supply of Li-ion batteries, the cost has dropped substantially over the course of a decade falling 89% (Henze, 2020) between 2010 and 2020. It is projected that further decreases in the price per kWh will come over the next couple of decades which would make the use of fully electrical aircraft more viable as a possible solution to reduce greenhouse gas emissions. Today the cost of batteries for use in electric aircraft remains high. Taking Eviation’s Alice as an example the aircraft is equipped with batteries totalling 820kWh. With a price of around $137 per kWh (Henze, 2020) in 2020 the cost of the batteries alone would be $112 340 out of an estimated total cost of around four million dollars (Narishkin & Appolonia, 2020). Through battery and material recycling the cost per kWh is suggested to become as low as $62 in the European Union 2020, $40 for each kWh in 2025, and even lower in large industrial countries such as China (Kavanagh, 2021). A reason why the shift towards more recycling have been slow is the yet to be fully matured recycling pathways, and comparably inexpensive raw materials. The price of raw material however is expected to increase as demand outpace supply (CNBC, 2021) later in the decade.

The cost of electricity varies from country to country depending on supply and demand. In 2020 the average cost of one kWh was €0.1254 with around 35% of the cost (Eurostat, 2020) being accrued from various taxes. Electricity costs is overall assumed to be lower than jet fuel, coupled with estimations of significantly less maintenance required compared to conventional aircraft, the operating costs for a fully electric aircraft is suggested to be less expensive by several multitudes (WSDOT, 2020). Taking Eviation’s Alice, the small regional aircraft seating 9 passengers, and comparing it with a representative counterpart such as the turboprop powered Pilatus PC-12, the electric aircraft is expected to have an hourly operating cost of around $200 whereas the PC-12 have an hourly cost of around $1000. The Swedish aircraft manufacturer Heart Aerospace claim that electric aircraft overall could reduce operating costs arising from fuel consumption by 50% to 75% (Heart Aerospace, 2021), and further states that electrical motors should require only a fraction of the maintenance compared to a conventional turboprop engine reducing cost by 90%.

Lower operating costs aside, the purchase cost for a new, or fleet of new electric aircraft most likely would be immensely capital intensive. Currently there are no mature concepts of retroactively equip current aircraft to become fully electric. An assumption can therefore be made that a widespread electrification of the global aircraft fleet would take place when contemporary aircraft have reached their end of service life to maximise the use of the large investment made.

Current envisioned electric aircraft often utilise propellers attached to their motors to produce propulsion. Propellers are often more efficient (El-Sayed, 2016), but are so at a lower forward speed compared to turbofan engines used extensively today. The slower speed mean that an average journey possibly would take longer than it is with current generation aircraft, removing some of the timesaving and convenience of flying whilst also reduce the number of flying sectors the aircraft could produce in a single day. There is a risk that this could result in higher fares for consumers at the same time as they get a longer journey. Positive research exist that suggest that consumer is willing to pay more for an airfare ticket (Read, 2020) if the increased cost is due to the operation being more sustainable.

5.5 ENVIRONMENTAL CONSIDERATIONS

The rapid shift in the automotive industry towards electric vehicles have been promoted as a mean of quickly and dramatically reduce the carbon footprint created from global vehicle use. Emissions from the cars themselves, often potent greenhouse gases, reduce overall but there are rising concerns surrounding the sustainability (CNBC, 2021) of a further electrified world reliant on battery technology.

5.5.1 Direct emissions

One of the main incentives as to why operators should choose an electric aircraft is because it produces practically no polluting emissions such as various greenhouse gases (Heart Aerospace, 2021). As there is no combustion of fossil fuels used for the creation of propulsion, there will be no direct discharges of carbon dioxide, nitrogen, or sulphur from the aircraft operations. Noise pollution is an issue that is sometimes overlooked but greatly impact the general population living in proximity of airports (Elliff, Cremaschi, & Envisa, 2020). Introduction of electric aircraft will most likely be able to reduce the noise characteristics especially during take-off and landing at airports close to cities and manufactures (Eviation, 2021) make it to a selling point.

5.5.2 Indirect consequences

Battery’s primary role is to store energy derived from electrical plants. The emissions from a fully electrical aircraft may not have any direct environmentally hazardous by-products, but the electrical plants supplying the aircraft with the electricity needed may be. As an example, many countries within the European Union still relies heavily on the use of conventional thermal (Eurostat, 2020), i.e., the burning of fossil fuels in the pursuit of electricity generation. A trend can however be seen where electrical plants using coal as fuel is decreasing slowly globally with a few exceptions (Carbon Brief, 2020). For electric aircraft to be truly environmentally friendly, the supply chain of the electricity being supplied must be monitored and potentially altered. But even with the emissions from electrical generation plants taken into consideration, the overall greenhouse gas emission reduction is expected to be positive compared to conventionally fuelled vehicles (Scott, 2020). Manufacturing of the commonly used Li-ion batteries are calculated to emit between 61 kg/kWh to 146 kg/kWh of carbon dioxide during production (Dahllöf & Emilsson, 2019). A reduction of carbon dioxide created during the production cycle of batteries have been noticed and explained through the increased demand in Li-ion batteries (Dahllöf & Emilsson, 2019). As demand have increased, the manufacturing pathways have become more efficiently utilised to maximise output. Further reduction is projected to be feasible assuming that the manufacturing paths begin to use more sustainable electricity from renewable resources such as wind and solar (Dahllöf & Emilsson, 2019), something that is relatively uncommon today. Another path to eliminate additional carbon dioxide emissions is to increase the amount of battery and material recycling. Energy operators estimate that the carbon dioxide emissions could be reduced with up to 90% (Fortum, 2021) if batteries where to be made using recycled materials.

5.6 SUMMARY

Fully electric automotive vehicles have become increasingly common globally, thus naturally an assumption could be made that other modes of transportation, including the aviation sector, could face a similar prospect of becoming electrified. In fully electric aircraft all the propulsion, and on-board ancillary systems must be powered by on-board batteries. Electric engines are highly efficient, around 90%, which is substantially higher than conventional combustion engines. The lack of any combustion of fuel makes the electric engines quieter, and devoid of any polluting emissions.

Energy storage is achieved by on-board batteries. There are many different types of batteries that are designed for different applications. Currently the most viable candidate for electrifying aircraft is Li-ion batteries. Li-ion batteries further comes in different variants with varying internal materials due specific design criteria, and material availability. Contemporary material selection for use in Li-ion batteries include lithium, nickel, manganese, and cobalt. The extraction, and subsequent yielding of some of these materials are energy intensive, polluting, and non-sustainable. Lithium is extracted from brine solutions and require extensive amounts of water to produce leaving local water supplies decimated or polluted. Nickel requires significant amount of energy to be produced, is linked to polluting emissions around the extraction sites and furnaces, and to create slag material. Manganese is poisonous to living organisms if subjected to it in higher concentrations. Reports show that high levels of manganese are found in the water supply surrounding the production lines and have been linked to intellectual impairment in younger populations. Cobalt requires significant amounts of energy to be extracted and refined, pollution from the cobalt production is linked to birth defects, and lasting breathing issues for inhabitants close it. Further, cobalt is found in large concentrations in the Democratic Republic of Congo where reports of child labour without protective equipment exist in the production.

One problem that hinders electrical aircraft to become widely adopted currently is the relatively low energy density of the batteries. Contemporary Li-ion batteries average around 200 Wh/kg, and studies suggest that an increase to around 500 Wh/kg is required prior to larger electrical aircraft can become a viable product and replacement to conventional aircraft. Availability of certain key materials used in current battery technology is projected to not being able to keep pace with increasing demand for the materials. As more products rely on batteries, the divergence of supply and demand might lead to increasing material prices, and unequal distribution around the world. Recycling of disused battery materials is starting to become a viable business model, and to satisfy future material demand.

Cost per kWh for batteries have fallen substantially through the last decade as the economics of scale from production facilities have increased. It is highly likely that a total shift towards electric aircraft will require an extensive and full restructuring of aircraft fleets, airport infrastructure, and electrical power generation requirements. This will most probably be a rather capital investment heavy endeavour. However, if a shift occurs, the operating costs will be low with electrical power being one factor, and reduced maintenance being another. Operating costs are suggested to fall by as much as 80% in some estimates.

The actual operation of electric aircraft will produce no emission in the form of carbon dioxide, nitrogen oxides, sulphur, particulate matter, or water vapor. Instead, the potential environmental impact would be from material production to be used in batteries, and electricity generation. A significant portion of the world's electrical supply is derived from fossil fuel sources that increase the amount of greenhouse gases emitted. If a shift in the power generation sector towards renewable energy such as solar and wind power, it can be assumed that electric aircraft will have an overall low environmental impact.

6 MOTIVATION FOR CHANGE

To minimise the impact on the environment, in particular considering greenhouse gas emissions, a significant change is required from the aviation industry. Actors include, airlines engaged in either passenger and freight operations, airports serving the airlines, and aircraft manufactures to name a few. It is often the case that dramatic changes to well established procedures and practices are not actively sought after as long as there is not something inherently wrong, or detrimental considerations to the current operation. The notion of “if it is not broken, don't fix it” is a common pitfall (Freeland, 2019). and encourage change prior to it becoming necessary. In the following section a brief examination of a couple of motivations for change is discussed. These include material availability, consumer demand, and regulatory incentives and regulations.

6.1 SUPPLY AND STRATEGIC SECURITY

Global interconnectivity has resulted in an increased amount of trade of goods and material being imported and exported to countries that might not have a specific resource physically available or being economically sustainable to them otherwise. Contemporary examples include crude oil, and certain minerals used in electric appliances such as batteries etc. The interconnectivity, increased dependence on receiving supplies just in time, and reduction of more costly manufacturing sources in certain regions create a vulnerability to disruptions. Recent events such as the global Covid-19 pandemic have laid bare the fragility of interconnectivity where goods and supplies fail to arrive when expected (Svensk Verkstad, 2020). Other potential scenarios with historical examples are global, or regional conflicts that can lead to a dramatic reduction of overall produced material, or through embargoes targeting specific countries or regions as occurred during the various so-called oil crisis that have happened during the last century (Kettell, 2014). Further, the European Union have identified 30 critical raw materials that the union currently have an import reliance on from various countries (European Commission, 2020). The motivation behind creating a list of critical materials is to pursue alternate sources that is more readily available within the union to safeguard against the possibility of reduced overseas production, or even embargoes.

6.2 CONSUMER DEMAND

Over the past couple of decades more consumers have increasingly been aware of the consequences of their behaviours and to the emission of various greenhouse gases. Pressure from close acquaintances or social norms can for example led to potential consumers electing not to fly in an attempt to reduce their personal emissions. For example, the Swedish term “flygskam”, directly translated to flight shaming, gained attention globally around 2018 aiming to change consumer behaviour and raise awareness of the emissions created when flying (Wolf & Abbugao, 2019). Additionally, if posed with the option between two similar products, one being less detrimental towards the environment, and one commonplace, a large proportion of the population would choose the product that created the lower amount of adverse environmental effects (White, Hardisty, & Habib, 2019). However, if the price for the two products is different, the choice becomes more divisive (Rice, Ragbir, Rice, & Barcia, 2020).

Studies show that a certain increase in the price that consumers pay to fly are possible but depends, among other things, on how much greenhouse gas emissions were to be reduced to justify the higher price point. Another consideration is the perceived increase in price if it were to occur from a higher baseline such as for longer international journeys. Aggregated data suggest that consumers expect to see a significant reduction in emissions to justify any increase in ticket prices (Rice, Ragbir, Rice, & Barcia, 2020).

6.3 CORSIA AND EU-ETS

The International Civil Aviation Organisation, ICAO, in 2016 agreed on a framework to measure, and reduce the impact of carbon dioxide emissions from the aviation sector (ICAO, 2016). This will be achieved by an offsetting scheme where airlines will be able to purchase emission credits from regional emission trading initiatives. The implementation is staggered, and the first phase became mandatory for all ICAO member states in 2019. From then all members are required to monitor, report, and verify how much carbon dioxide is being emitted due to its’ international air traffic (ICAO, 2019). Between 2019 and 2020 a baseline was created by measuring how much carbon dioxide was being produced by international air traffic. If, for example, an airline was to emit a larger quantity of carbon dioxide than the baseline, it is expected to purchase emission credits to compensate. The credit rate is calculated to be that for every metric tonne of carbon dioxide emitted, one credit must be purchased (ICAO, 2019). Proceeds from the transaction will be allocated to carbon dioxide reducing investments such as reforestation, investment in new less polluting technology, and research. From 2021 a voluntary preliminary phase will begin to evaluate the program with emission credits, and a large majority ICAO’s member states, responsible for roughly 77% of the global aviation traffic, have indicated that their intention is to participate. Remaining large air traffic market and carbon dioxide producers such as China, India, Russia, etc. will join the CORSIA emission program when it becomes mandatory internationally in 2027 (Jozsa, et al., 2019). In an effort to motivate airlines to begin a shift towards new and cleaner technologies, certain types of approved fuels and propulsion methods will attract a reduction in the number of credits required to compensate for emissions (Jozsa, et al., 2019). A prerequisite is that the alternative fuel shall emit at least 10% less carbon dioxide and not be taken from biomass that contains large amounts of stored carbon.

The European Union already have a similar system adopted initially in 2003 called the EU Emissions Trading System, EU-ETS. The two systems have a lot of commonality, and within the European Union CORSIA compliance for the aviation sector is being fulfilled via the already established emissions trading system (Palmqvist, 2020). In the systems emitters of carbon dioxide, nitrous oxide, and perfluorocarbons are given a certain amount of emission points that can be used during one calendar year (European Commission, 2016). If the allocated points are not sufficient to cover the operator’s business during the year, a remaining pool of points are available to an auction where all operators can participate. Allotted free points to a given polluter are reduced every year to encourage a transfer towards less polluting operating methods. If during a year, one operator does not utilise all their acquired points, they may either keep the excess for an upcoming year or sell them to other operators at a market driven price point, again creating a monetary incentive for operators to reduce their emissions.

6.4 RED II

The European Union in 2018 revised a previous ambition to reduce the amount of greenhouse gases emitted from electricity generation, heating, and the transportation sector. The initiative is called the Renewable Energy Directive, RED, and is the second iteration of a previously adopted European resolution. One of the goals are for the entire union to reduce the quantity of emissions produced by increasing the amount of renewable energy to at least 32% out of the total energy demand before 2030. Within this the transportation sector is required to achieve at least 14% of its’ energy consumption by means of renewable sources (Jozsa, et al., 2019). A large change from the previous agreed resolution is that the responsibility to achieve the change is shifted from the individual member states, and instead placed on the various fuel and energy producers operating within the EU. To define the rules of what is considered renewable certain criteria were incorporated. To be classified as renewable and sustainable the fuels used for energy consumption must limit or reduce the amount of greenhouse gases being produced, not pollute the environment, consider continued biodiversity, social issues, local and regional food prices, and the overall use of land required to produce the fuel (Bitnere, 2017).

The directive’s ambition is to guide the transportation industry to reduce emissions through various directed incentives where fuel providers can claim a higher amount of fuel supplied to reach the goal but only if satisfying certain criteria. For example, to motivate the car industry and fuel providers to reduce the dependency on fossil fuels the fuel providers would be able to claim four times the energy delivered to cars if it is provided as electricity (Jozsa, et al., 2019). For the aviation sector the multiplier is only 1.2 and the significantly lower multiplier compared to the car industry have attracted concern and criticism. (IATA, 2018) The main criticism being that fuel providers will focus their research and development towards other sectors such as the car industry due to the big multiplier difference. Critics fear that this will delay the upscaling of renewable fuels that can be used in the aviation sector and through that keep alternative fuel prices high for a long period of time to come.

7 CONCLUSIONS

Today the practically universally adopted energy storage method for the aviation sector is through conventional jet fuel that have a high energy density. Having a high energy density is important in aviation as weight is a great concern where lower weight of an aircraft will enable lower fuel consumption, greater commercial payload to be carried, and range to be extended. All of the surrounding and associated infrastructure is designed with the properties of jet fuel in mind. This includes raw material extraction, refining, transportation, and fuel storage. Raw material for the subsequent production of jet fuel is crude oil, which is a fossil, non-renewable energy source. When the jet fuel is consumed in contemporary gas turbine engines significant emission occur with predominantly carbon dioxide, nitrogen oxides, sulphur, particulate matter, and water vapor. All these emissions are so-called greenhouse gases and are considerable contributors to a global warming effect on the atmosphere.

At the beginning of the research undertaken in this report, the author wanted to find answers to three main questions through literature studies. These questions are once again asked and discussed in the sections below.

7.1 ENERGY STORAGE METHODS

> *What type of energy storage methods exist today, and in the short to medium term that could potentially be suitable for use in aviation?*

During the collection and compilation of various sources, four broad types of energy storage is possible in the near to medium term. These include continued use of conventional jet fuel, sustainable aviation fuels, hydrogen stored in liquid form, and fully electric aircraft using batteries. Whilst assembling the information for this research report it is clear that there are many positive, and negative attributes to the various energy storage systems. Therefore, there is no absolute crystal-clear immediate solution for a dramatic change in aviation as no consensus of what the future might hold exist yet in the industry.

Taking sustainable aviation fuel as the first example, the fuel is in many ways meant to offer a more direct replacement to conventional jet fuel compared to other energy storage means. Compared to jet fuel, sustainable aviation fuels are produced from renewable resources that come from various sources such as specifically grown crops, and waste materials instead of crude oil. Like jet fuel though is that sustainable aviation fuel still contains carbon and will subsequently emit carbon dioxide. An important distinction is that the source material is renewable, and through that allows for a more closed carbon lifecycle can be accomplished. Material used in the production of sustainable aviation fuel can also be grown or cultivated in land areas that are otherwise inhospitable to other crops or uses and have been identified as a potential source to increase prosperity in areas that otherwise would be less desirable. As of today, it is not possible from a regulatory point of view to operate aircraft using only sustainable aviation fuel. Instead, it must be mixed with conventional jet fuel with a maximum blend of 50%. One reason for why it is not possible to use a higher blend is likely because of regulatory caution where studies suggest that some of the sealing properties inside of the aircraft fuel systems can be compromised with too high levels of sustainable aviation fuels and their lower aromatic content. However, even a mixed fuel content will create a beneficial environmental impact through reduced emission. Assuming future regulatory approval for higher blends, possibly up to 100%, environmental impacts will reduce drastically. One can foresee that use of sustainable aviation fuels will become substantially more widespread in the near future as it can acts as a direct replacement to conventional jet fuel whilst creating a tangible positive environmental impact.

Hydrogen used in its’ liquid supercooled form appear to be a potentially disruptive new technology in the near to medium term with large actors such as Airbus claiming that they will create a new generation of aircraft powered by hydrogen. In liquid form hydrogen have a higher energy density compared to jet fuel but require significantly more storage volume. So even though hydrogen in theory can operate contemporary gas turbine engines, a direct replacement like sustainable aviation fuels seems unlikely as extensive modification would be required, not least where and how to store the hydrogen effectively.

A large motivation as to why hydrogen is interesting is that it would be near emission free when consumed in potential aircraft. When used in a gas turbine engine, no greenhouse gas emissions are created except for reduced levels of nitrogen, and increased amounts water vapor which in turn can create contrail formations. If instead the hydrogen is consumed through fuel cells to generate electricity, the resulting emission would only be in the form of water vapor. Contrail formation can be reduced by altering the aircraft cruising levels to lower altitudes where condensation of the vapor is less likely to occur.

The actual process of producing suitable concentrations of hydrogen is an energy intensive process where the majority currently is produced using polluting methods. If use of hydrogen becomes more widespread, an improved production process is required at large scale as to avoid only shifting the source of greenhouse gases from the aircraft to fuel manufacturing. Green hydrogen does not use any fossil fuels during its’ production but are instead using electricity from renewable resources, sources that will have to be expanded massively globally to keep up with the estimated increase in demand for green energy.

The last new technology that could invoke a shift in aircraft energy storage is on-board batteries supplying electricity to electric motors and other systems. Like hydrogen, the use of batteries would dramatically reduce the quantity of emissions created. But where hydrogen still emits water vapor, batteries does not create any emissions at all making them the most environmentally friendly option discussed previously from an operational point of view. With that being said, the materials required to manufacture the batteries envisioned to be used in electric vehicles are not always sustainable. Certain material creates intense pollution in the area surrounding the manufacturing facilities and can create serious health issues to living organisms. In comparison to sustainable aviation fuel, future electric aircraft might be able to be retrofitted onto more conventional designs that are in use currently with either jet fuel or sustainable aviation fuel. However, as there will be substantial modifications to the aircraft, it cannot be counted as a direct replacement. With that being said, it most likely would involve less of a technical hurdle to make aircraft fully electric compared to being run on hydrogen since hydrogen requires novel fuel storage tanks, fuel system, and associated modifications. Current batteries have increased in efficiency and energy storage as more and more battery powered appliances have emerged globally. But the current energy density of around 200kWh/kg is still not deemed to be sufficient to power aircraft where a target is more likely around 500kWh/kg.

In summary, it is possible to imagine a future scenario where all the discussed technologies are being used at the same time whilst either phasing in or out older, and newer aircraft. Conventional jet will most probably remain an international standard in the near term due to a well-developed global infrastructure covering manufacturing, transportation, and storage. However, seeing that sustainable aviation fuels are a direct replacement with only minor modifications required, it is likely that a gradual shift towards higher blends, or more widespread use in aviation can occur in the near term as well. This however requires the supply of sustainable aviation fuel to increase to meet demand, and possible also to start to reduce the purchase price to further encourage uptake of the new fuels. Electric aircraft is suggested to be furthest in development compared to hydrogen as the next evolutionary step in aircraft energy storage. It is possible that as electric vehicles become more widespread, especially motor vehicles, that technological breakthroughs can be translated into more feasible aircraft designs. As it stands now with batteries possessing a relatively low energy density, the likely market and operations could be narrow with especially low demand and short routes can adopt electric aircraft first. To fly routes like those today, hydrogen is probably a better solution to batteries as the energy density is substantially higher whilst also being very environmentally friendly. The technology for electric and hydrogen aircraft is however not suitable for commercial application in the near term, but it is highly likely that it will become ready in the medium term with increasing interest in how to reduce greenhouse gases quickly, whilst at the same time maintaining global connectivity.

7.2 MOTIVATORS FOR CHANGE

Which types of drivers, or motivators, exist for the aviation sector to adopt newer and more sustainable technologies?

Beyond the arguable socially responsible course of action to engage in quick and decisive reductions in greenhouse emissions, some other factors will most likely also play a role in motivating the aviation industry to change energy storage methods. One reason is a greater degree of stability in terms of energy supply from new sources. Crude oil used to create jet fuel is generally limited to certain regions globally, an interruption of any kind can adversely affect the entire international community. A shift towards sustainable aviation fuel, hydrogen, or battery powered vehicles can most often be sourced more locally or at the very least on a regional level such as within the European Union.

Changing population sentiment and consumer demands for more environmentally friendly transportation will probably also play a big role in a future change. There has been a growing general concern in the wider populace about the effect of climate change which have led to a certain reduction in flying in some markets. If the aviation sector were to be proactive and show that they are taking meaningful and proactive measures to combat climate change, a possible positive shift in mentality could occur. It is almost guaranteed that a shift in energy storage technology will make flying more expensive, but studies suggest that a significant majority of the population is willing to pay a premium, up to a reasonable amount, for more environmentally friendly travel.

Lastly, strictive regulations are already occurring globally and regionally aiming to reduce the environmental impact derived from the transportation sector. Measures include taxation on emissions, mandates on fuel mixtures, and could potentially include complete bans on certain types of fuels in the future. In here one could foresee an economical incentive for early adopters of new technology as they would have to pay less taxes, and potentially see an increase in their market share.

7.3 BARRIERS FOR IMPLEMENTATION

Are there any barriers to quick and widespread adaptation of the new technology?

Current international regulatory framework is created around the fact that most aircraft use conventional jet fuel. Recently the use of sustainable aviation fuels has garnered increasing interest to replace jet fuel as it is more environmentally sound. However, present regulations only allow a certain portion of sustainable aviation fuel to be used, at most up to 50% when combined with jet fuel. A review of those regulations to allow for a higher blend up to 100% would be recommended to allow for further adaptation. If greater volumes could be used in aviation, the supply should also increase as it would become more economically viable for fuel producers to allocate funding for capital investment. As it stands right, the supply of sustainable aviation fuel is only a fraction of what would be required to facilitate a complete shift from jet fuel.

Like sustainable aviation fuels, hydrogen is not produced at the substantial amount required to satisfy a complete adoption of it as an energy storage method. The hydrogen that is currently produced is also not made in a sustainable manner and emits significant amounts of emissions. For hydrogen to be a feasible new technology to be applied in aviation, new aircraft design and fuel storage solution must probably first be achieved. Retrofitting current aircraft is expected to be cost ineffective and lack overall energy efficiencies. Further, if green hydrogen or battery powered aircraft will dominate in the future, major investment into renewable electricity must be made to support the increasing electric demand. The process of installing new electrical capacity is required to begin quickly to meet the expected future increasing demands.

Batteries that are produced today contain significant number of rare materials that are sometimes hard to source locally. Instead, certain materials are produced in specific global regions and are sometimes subject to unsustainable manufacturing processes. So, if battery powered aircraft is to become a viable solution, large technological breakthroughs in terms of material selection, and energy density in batteries must be made, as well as devising a solution on how to allow for quick energy replenishment for aircraft. This could be either through advanced quick charging, or by designing swappable batteries.

7.4 PROPOSED FURTHER RESEARCH

The amount of time available for the international community to decisively act on the issue of adverse climate change is quickly dwindling. As described in this report, various technologies could potentially minimise, or even eliminate, some of the environmental impacts that the aviation sector create. However further research is recommended to gain a better understanding of what the best course of action moving forward is. Below are some recommendations for future research.

- How can a global shift to a new technology best be solved quickly, and efficiently?
- What type of standardisation is required in terms of energy storage methods, production, transportation, and physical storage etc.?
- Is there a case for government intervention to regulate the use of jet fuel, and to subsidies new technologies instead?
- Are current regulations surround the certification of aircraft using new technology to stringent, and is this a hindrance for disruptive technology?
- Will new technology be compatible with current training and certification requirements for air crew, maintenance personnel etc., or is retraining required?

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