The Future of Advanced Bio-Jet Fuel

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The aviation industry is growing rapidly and the carbon dioxide emissions from the industry are following in the same manner. Biofuels made from edible feedstock have had an impact on lowering the emissions but at the same time an impact on increasing food prices. There are a few alternative fuels on the market today (TF-SPK, HEFA-SPK) which work in a blend with the petroleum based fuels, reducing the emissions from the aircrafts. Biofuels from next generation biomass, also called advanced biomass, such as algae and lignin, seem likely to be a good substitute for the first generation biofuels. The advanced biofuels are relatively costly to produce. This is due to the many steps in the production process, which restricts the usage of these sorts of fuels in the aviation industry. There are some problems associated with a jet fuel produced from 100% biomass. This is because the jet fuel produced from biomass differs from the jet fuels used today, making it unsafe to use in modern day airplane engines. That is why it is important to find an alternative jet fuel based on biomass that has the same characteristics as the conventional jet fuel, to be able to use the same transportation and engines that are in use today. Otherwise the high cost of advanced bio-jet fuels will make them unusable.
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1 Abstract

The aviation industry is growing rapidly and the carbon dioxide emissions from the industry are following in the same manner. Biofuels made from edible feedstock have had an impact on lowering the emissions but at the same time an impact on increasing food prices. There are a few alternative fuels on the market today (TF-SPK, HEFA-SPK) which work in a blend with the petroleum based fuels, reducing the emissions from the aircrafts. Biofuels from next generation biomass, also called advanced biomass, such as algae and lignin, seem likely to be a good substitute for the first generation biofuels. The advanced biofuels are relatively costly to produce. This is due to the many steps in the production process, which restricts the usage of these sorts of fuels in the aviation industry. There are some problems associated with a jet fuel produced from 100% biomass. This is because the jet fuel produced from biomass differs from the jet fuels used today, making it unsafe to use in modern day airplane engines. That is why it is important to find an alternative jet fuel based on biomass that has the same characteristics as the conventional jet fuel, to be able to use the same transportation and engines that are in use today. Otherwise the high cost of advanced bio-jet fuels will make them unusable.

2 Background

The avian industry has grown rapidly and the use of jet fuel has followed in the same manner of growth, leading to a great negative impact on the greenhouse gas effect (Jiménes-Díaz et al., 2017). Two percent of the global man made carbon dioxide emissions are from aviation emissions (Air Transportation Action Group, 2012). However, due to the current rapid growth within the aviation industry the carbon dioxide emissions are predicted to have a similar rapid increase leading to increases of greenhouse gases in the atmosphere (Air Transportation Action Group, 2012). Boeing released a market research outlook in 2016 where they predicted a growth in passenger traffic by 4.8 % within the next 20 years (Boeing, 2016). Due to the great impact on the climate the aviation industry has set up a few targets and one of them is to decrease the carbon dioxide emission by 50% by 2050 (Air transportation Action Group, 2012). The most commonly used aviation fuel in, at least, commercial aviation fuels are jet fuels, and today most of those jet fuels are petroleum based (Hileman and Stratton, 2014; Liu et al., 2013). Petroleum is a type of crude
oil which consists of a mixture of hydrocarbons (Hileman and Stratton, 2014; Liu et al., 2013).

There are fuels which do not produce as high amount of carbon dioxide emissions (Gronenberg et al., 2013; Liew et al., 2016). Hileman and Stratton (2014) managed to show that it is possible to significantly lower the total amount of carbon dioxide emissions from transportation fuels by switching to a different type of fuel (Hileman and Stratton, 2014). These types of fuels are based on different types of biomass which are produced through photosynthesis (Hileman and Stratton, 2014). The released carbon dioxide from using these types of fuels will thus have a net combustion of zero (Hileman and Stratton, 2014). These types of fuels are called biofuels and are normally produced by different types of biomass such as rapeseed oil or bio-waste (Gronenberg et al., 2013; Liew et al., 2016). It is the economic and environmental sustainability, energy supply diversity and competition for energy resources that are the main driving forces for the development of the different types of biofuels (Hileman and Stratton, 2014).

There are two different types of biofuels, first generation biofuels and next generation biofuels, also called advanced biofuels (Gronenberg et al 2013). The first generation biofuels are normally produced from edible feedstock such as rapeseed, corn or sugarcane (Daroch et al., 2013; Fairley, 2011). This method of creating biofuels from edible feedstock has, however, been shown to have impacts on the increasing food prices (Daroch et al., 2013; Fairley, 2011). When producing ethanol or biodiesel, it is normally done on first generation biofuels (Schubert, 2006). Some of the complications with first generation biofuels are: food price issues, land and water usages and pollution (Air Transportation Action Group, 2012). The advanced biofuels are however based on unpalatable feedstock such as lignocellulose, which is the woody parts of plants (Daroch et al., 2013; Schubert, 2006). The lignocellulose has an abundant source of energy and lignocellulose is everywhere, trees, cornhusks or wheat straw are just a few places where lignocellulose can be found (Schubert, 2006). Biofuels made from feedstock such as lignocellulose have been shown to provide several benefits to society (Balan, 2014). Biofuels from lignocellulose are renewable and sustainable, they have also been shown to reduce air pollution as there would be less burning of the biomass (Balan, 2014). The main problem with producing advanced biofuel is that it requires high investment costs, due to the complexity of the conversion of the different biomasses, and they are more expensive than first generation biofuels (Fairley, 2011; He and Zhang, 2011; Wingren et al., 2008).
Jet fuels based on biological sources would lower the carbon dioxide emission and the advanced biofuels would be an ideal solution, due to the complication that lies with first generation biofuels (Air Transportation Action Group, 2012). However, jet fuels have not completely been replaced by bio-jet fuels, due to the fact that jet fuels differ from the traditional transportation engine fuels (Cheng and Brewer, 2017; Kallio et al., 2014).

3 Material and Methods

This thesis is a literature study. The literature was found through searches through Linköping’s university’s library search page, Scopus, and google scholar. Search words such as jet fuel, bio-jet fuel, advanced biofuel, lignin, and algae were used.

4 Types of Jet Fuel

Jet fuels consists of a mixture of hydrocarbons which includes; paraffins, branched alkanes, cycloalkanes and aromatics (Corporan et al., 2011; Dagaut and Cathonnet, 2006; Jiménes-Díaz et al., 2017; Vukadinovic et al., 2013). It is the different ratio of these hydrocarbons that make up the different jet fuel types (Corporan et al., 2011; Dagaut and Cathonnet, 2006; Jiménes-Díaz et al., 2017; Vukadinovic et al., 2013). The hydrocarbon number range should be within the range of C8-C16; this specific range is needed to give jet fuel its high yield and low freezing point (Kinder and Rahnes, 2009; Verma et al., 2011). For the jet fuel to be able to work in the engine several requirements need to be met, which can be found in Table 1 (Corporan et al., 2011; Verma et al., 2011).
Table 1. The importance of the different characteristics of jet fuel (Hileman and Stratton, 2014; Cheng and Brewer, 2017)

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Importance</th>
</tr>
</thead>
<tbody>
<tr>
<td>High energy per unit volume (also known as high energy density)</td>
<td>Simplifies long range flights</td>
</tr>
<tr>
<td>High energy per unit mass (also known as high specific energy)</td>
<td>Improves fuel effectiveness and decreases the takeoff weight</td>
</tr>
<tr>
<td>High flash point. This indicates the temperature which the fuel produces vapor that can ignite</td>
<td>Guarantees safe maneuver of the fuel</td>
</tr>
<tr>
<td>Low freezing and vapor point</td>
<td>This is important for safe flights at the high altitudes where the planes are operating</td>
</tr>
<tr>
<td>High thermal stability</td>
<td>Prevents fuel blockage</td>
</tr>
<tr>
<td>Suitable lubricity</td>
<td>Ensures that the fuel pumps function properly</td>
</tr>
<tr>
<td>Suitable aromatic content</td>
<td>Prevents seal swell within the fuel system, important for the avoidance of fuel leaks</td>
</tr>
</tbody>
</table>

One of these requirements is that the fuel heat of combustion should be higher than 42.8 MJ kg\(^{-1}\) and viscosity should be lower than 8.0 mm\(^2\) s\(^{-1}\). Another important requirement of the characteristics of the jet fuel is the hydrogen to carbon ratio, this ratio has an impact on the specific heat of the fuel at a constant volume and pressure (Bester and Yates, 2009). In Table 2 the different characteristics of three different types of jet fuels are presented, Jet A (used in commercial flights in North America), Jet A-1 (used in commercial flights in Europe) and JP-8 (a type of fuel used in military airplanes) (Bi et al., 2015; Corporan et el., 2011; Elmoraghy and Farag, 2012; Lobo et al., 2011).
Table 2. Some of the different types of jet fuels and their characteristics (Bi et al., 2015; Elmoraghy and Farag, 2012; Lobo et al., 2011).

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>Heat of combustion (MJ/kg)</td>
<td>43.3</td>
<td>43.3</td>
<td>43.0</td>
</tr>
<tr>
<td>Freezing point (°C)</td>
<td>-40</td>
<td>-47</td>
<td>-49</td>
</tr>
<tr>
<td>Kinetic viscosity at – 20 °C (mm²/s)</td>
<td>5.78</td>
<td>4.27</td>
<td>4.10</td>
</tr>
<tr>
<td>Hydrogen content (wt.% )</td>
<td>13.6</td>
<td>13.7</td>
<td>13.7</td>
</tr>
<tr>
<td>Total oxygen (wt.% )</td>
<td>0</td>
<td>0</td>
<td>-</td>
</tr>
<tr>
<td>Total sulfur (wt.% )</td>
<td>&lt;0.3</td>
<td>&lt;0.3</td>
<td>0.064</td>
</tr>
<tr>
<td>H/C (mol ratio)</td>
<td>1.92</td>
<td>1.92</td>
<td>1.92</td>
</tr>
</tbody>
</table>

Sulfur, nitrogen, and oxygen are all components that can affect the jet fuels performance in a negative way (Hileman and Stratton, 2014; Kinder and Rahms, 2009). These impurities, as well as different types of metals, should be kept to a minimal (Kinder and Rahms, 2009). Aromatic and sulfur content in jet fuels impact air quality negatively (Hileman and Stratton, 2014). If a change of the fuel composition, which would reduce the aromatic and sulfur content in jet fuel can be made then it would give the aviation industry a less negative impact on the air quality (Hileman and Stratton, 2014).

Renewable transportation fuels which are used for ground transportation such as biodiesel and ethanol cannot be used in aviation fuel (Air Transportation Action Group, 2012; Hileman and Stratton, 2014). Biodiesel used for ground transportation will freeze at the high altitudes, and ethanol does not meet the requirements of the energy density which is needed (Air Transportation Action Group, 2012; Hileman and Stratton, 2014).

In the jet engines, soot particles must be kept to a minimum as soot can be harmful for the mechanical compartments of the engine (Dagaut, 2005). Soot can lead to carbon deposits and radiant heat loss which can lead to hot spots combustor wall temperatures that are too high (Dagaut, 2005). The engines soot emissions will also have an effect on the radar detection of military jets making them more visible (Dagaut, 2005). Fuels with high aromatic contents produce more soot and this is why the amount of aromatics must be limited in jet fuel (Dagaut, 2005). However, a low amount of aromatics could lead to seal swell which would lead to fuel leaks in the airplane systems, thus aromatics are still needed to be a component of jet fuel (Corporan et al., 2011; Hileman and Stratton, 2014; Liu et al., 2013). Alkyn-benzens, which are types of aromatics, with a low molecular
weight are desirable because they cause less soot combustion than other types of aromatics (Cheng and Brewer, 2017). The aromatic content of the jet fuel also has an influence on the hydrogen to carbon ratio (Bester and Yates, 2009).

5 Alternative Jet Fuels

There are several different types of renewable jet fuel alternatives at use in the market at the moment: Fischer-Tropsch synthetic paraffinic kerosenes (TF-SPK), biomass-derived synthetic paraffinic kerosenes (Bio-SPK) are the most common (Corporan et al., 2011; Jiménes-Díaz et al., 2017; Pearlson et al., 2013; Yao et al., 2017). However, there are renewable jet fuels techniques that are up and coming and has been tested for use in jet engines, the technique is called alcohol to Jet Synthetic Paraffinic Kerosene (ATJ-SPK) (Jiménes-Díaz et al., 2017).

To produce jet fuel from biomass, high temperatures are required for the hydroisomerization and the hydrocracking (Verma et al., 2011). This is typically used when producing 8C-15C hydrocarbons (Verma et al., 2011). Hydroisomerization and hydrocracking is used when longer hydrocarbons need to be shortened (Bauer et al., 2014; Kallio et al., 2014). The hydroisomerization is used when producing the branched alkanes which are important for lowering the boiling point and freeze point (Jiménes-Díaz et al., 2017; Moser, 2010).

5.1 Fischer-Tropsch Synthetic Paraffinic Kerosenes (FT-SPK)

Fischer-Tropsch synthetic paraffinic kerosenes (FT-SPK) is a method that uses lignocellosic biomass to produce bio-jet fuels (Liu et al., 2013; Bi et al., 2015). In this process the biomass is transformed into bio-syngas which then goes through a Fischer-Tropsch synthetic (FT) process and gets transformed into biofuels (Corporan et al., 2011; Liu et al., 2013; Bi et al., 2015). In FT-SPK the biomass must go through gasification which turns the biomass into bio-syngas (Corporan et al., 2011; Bi et al., 2015). Gasification is a process which reacts pyrolysis products with either air or steam to transform bio-syngas (Liu et al., 2013). Pyrolysis products are products which are produced in the absence of oxygen by direct thermal decomposition of the biomass (Liu et al., 2013). Bio-syngas consists of hydrogen gas and carbon monoxide which are converted into hydrocarbons through the FT process (Liu et al., 2013).
The FT process is a chemical process which uses a catalyst to react carbon monoxide and hydrogen to make paraffins (Bi et al., 2015; Hileman and Stratton, 2014; Kinder and Rahms, 2009; Kumabe et al., 2010; Moses, 2008; Yan et al., 2013; Corporan et al., 2011). The first step of the FT process is hydrodeoxygenation; this is done to remove oxygen which is removed as water (Jiménes-Díaz et al., 2017; Perlson et al., 2013). The deoxygenated products will be separated by distillation and the heavier molecules have to be hydrocracked; this is because the normal length of the hydrocarbons you get from hydrodeoxygenation is C17-C18 (Jiménes-Díaz et al., 2017). Hydrocracking these components will make them within the desired length for jet fuel (Jiménes-Díaz et al., 2017). Next selective hydroisomeration and catalytic cracking are performed on the sample, followed by an addition of cooling water to cool the samples (Perlson et al., 2013). The different products are then separated into the different fuel types, the gas is recovered and hydrogen is produced (Perlson et al., 2013). The hydrogen can then be reused in the hydrodeoxygenation step (Perlson et al., 2013). For the final step the products are stored and blended (Perlson et al., 2013). Figure 1 is a simplified picture of the different FT process stages.

![Figure 1. The different stages of the FT production, going from left to right. Within the rectangles are the main FT production with hydrodeoxygenation, isomerization and catalytic cracking, and separation, which then leads to the different types of fuel (Perlson et al., 2013).](image)

This technique is approved for use in commercial jet fuels (Bi et al., 2015; Hileman and Stratton, 2014; Kinder and Rahms, 2009; Kumabe et al., 2010; Moses, 2008; Yan et al., 2013). FT-SPK contains a large amounts of paraffins (hence the name) and the neat combination of the paraffins has shown that these fuels produce a lower amount of soot than petroleum.
based jet fuel. When comparing with JP-8 which is a type of military fuel (Corporan et al., 2011).

5.2 Biomass-Derived Synthetic Paraffinic Kerosenes (HEFA-SPK)

Biomass-derived synthetic paraffinic kerosenes (HEFA-SPK) are produced from vegetable oils and fats from animals (Perlson et al., 2013). These oils and fats are transformed into fuels which have the same characteristics as the petroleum based fuels (Perlson et al., 2013). Plants such as algae, jatropha, rapeseed and camelina can be used as biomass base for HEFA-SPK (Rahmes et al., 2009). HEFA-SPK is hydroprocessed esters and fatty acids (Baena-Zambrana et al., 2013; Schroecker et al., 2011). This technology is commonly referred to as oil-to-jet (Jiménes-Díaz et al., 2017).

The FT-SPK process and the HEFA-SPK method are similar processes they both go through the FT process (Baena-Zambrana et al., 2013; Kinder and Rahmes, 2009). The main differences in the two different processes are that no gasification is needed for the production of HEFA-SPK (Hileman and Stratton, 2014). Instead the HEFA-SPK derives jet fuels from the biomass oils which are produced into paraffin wax (Hileman and Stratton, 2014; Baena-Zambrana et al., 2013). Due to that both the FT-SPK and HEFA-SPK go through the FT process the final products are extremely similar in components (Baena-Zambrana et al., 2013).

Test flights with HEFA-SPK produced jet fuels showed a decreased fuel flow which did not impact the flight due to an increase in energy density per unit mass, this indicates that a flight powered by a HEFA-SPK blend could last longer with the use of less fuel (Kinder and Rahmes, 2009). The test flights did not show anything different than normal flights, showing that a HEFA-SPK blend could be used in commercial flights (Kinder and Rahmes, 2009).
5.3 Alcohol to Jet Synthetic Paraffinic Kerosene (ATJ-SPK)

Alcohol to Jet Synthetic Paraffinic Kerosene (ATJ-SPK) is the process where alcohol is transformed into jet fuel (Yao et al., 2017). This jet fuel is produced from biomass which has a high sugar content, is starchy and lignocellulosic (Yao et al., 2017). The sugars from these biomasses are fermented into ethanol or other alcohols and it is these alcohols that can be transformed into jet fuel (Yao et al., 2017). The conversion into jet fuel is done by upgrading the short chain alcohols and the long chained fatty alcohols (Jiménes-Díaz et al., 2017).

This process can be used to transform ethanol, n-butanol or iso-butanol into jet fuel (Wang and Tao, 2016). The ATJ process has three main steps; alcohol dehydration, oligomerization, and hydrogenation (Wang and Tao, 2016; Yao et al., 2017).

Dehydration is needed to produce alkanes which then is oligomerized (Wang and Tao, 2016). The oligomerization is done to produce heavier alkanes from the alkanes produced from the dehydration (Wang and Tao, 2016). Hydrogenation is needed to get these heavier alkanes into the hydrocarbon range which is needed for jet fuel (Bi et al., 2015; Wang and Tao, 2016). The hydrogenation reduces the number of double bonds (Bi et al., 2015, Prak et al., 2015).

Test flights were done successfully with ATJ jet fuel in 2012 and in March, 2016 the ATJ production was approved for up to a 30 % blend with petroleum based jet fuels and can be used in commercial flights (EcoSeed, 2012; Yao et al., 2017).

5.4 Blending With Petroleum Based Fuels

The renewable jet fuels in Sections 5.1, 5.2, 5.3 all contain mostly n-and iso-paraffins, and have nearly no aromatics or cycloalkanes within the range required for jet fuel (Corporan et al., 2011; Dupain et al., 2005; Robota et al., 2013). Due to the lack of aromatics and cycloalkanes bio-jet fuel needs to be blended with petroleum based jet fuels, for the biofuels to be allowed to be used as aviation fuels (Hileman and Stratton, 2014; Lobo et al., 2011). These 50/50 blends still contain less aromatics in the fuel blend which reduces the aviation industries impact on the air quality (Bester and Yates, 2009; Hileman and Stratton, 2014; Huber et al., 2006).
The renewable biomass derived jet fuels are nearly sulfur free, so a blend with petroleum based fuels gives a reduced sulfur content (Hileman and Stratton, 2014; Huber et al., 2006).

Both aromatics and cycloalkanes are important components in jet fuel; aromatics should be around 10-15% of the fuel and cycloalkanes are the second most abundant component after paraffins (Vulkadinovic et al., 2013). Alkyl-benzens with a low molecular weight is desirable in renewable jet fuels because they cause less soot combustion than other aromatics (Cheng and Brewer, 2017).

The jet fuel has not completely been replaced by bio-jet fuels because jet fuels differ from the traditional engine fuels (Cheng and Brewer, 2017; Kallio et al., 2014). It is however the lack of aromatic and cycloalkane hydrocarbons in bio-jet fuel that is the main problem (Cheng and Brewer, 2017; Hileman and Stratton, 2014). In order to make a 100% bio-jet fuel, a biosource must be found where you are able to synthesize aromatics and cycloalkanes fuel compounds (Cheng and Brewer, 2017). Theoretically these components can come from cellulosic biomass which would give a fully synthetical jet fuel (Hileman and Stratton, 2014).

6 Feedstock

6.1 Algae

Oil from algae is one of the oils that can be used in the BIO- SPK process (Elmoraghy and Farag, 2012; Hussain and Naryan, 2017; Kallio et al., 2014; Robota et al., 2013; Savage, 2011; Su et al., 2017). Algae are a photosynthesizing organism needing carbon dioxide, water and sunlight to be able to grow (Savage, 2011). Algae can grow in polluted water, water which is not suitable for drinking or for use in agriculture (Kinder and Rahms, 2009). The algae can be grown in closed or open ponds in salt or in brackish water (Hussain and Naryan, 2017). Algae has a high growth rate and can be harvested for oil which can then be processed into biofuel (Huber et al., 2006; Kinder and Rahms, 2009).

High costs in producing algae is the main limitation for the usage of algae oil (Huber et al., 2006). The high costs include carbon dioxide costs, the large area it needs to be able to grow, and the many steps of the algae to oil process (Hileman and Stratton, 2014; Huber et al., 2006; Patil, 2008).
The cost has been estimated to be about 200 dollars per metric ton which is higher than the cost of the biomass lignocellulose, which has been estimated to about 40 dollars per metric ton (Huber et al., 2006). Algae needs concentrated carbon dioxide to grow via photosynthesis, and the amount of carbon dioxide is estimated to be one fourth of the cost of the production of algae (Hileman and Stratton, 2014; Huber et al., 2006). To produce 1 kg of algae biomass you would need 1.6-1.8 kg of carbon dioxide (6.2 kg CO2/kg biodiesel) (Elmoraghy and Farag, 2012; Patil, 2008). However, the cost can be lowered by using waste carbon dioxide from fossil fuel plants, it would be an advantage for the big scale algae productions to get their carbon dioxide contribution from nearby powering plants (Elmoraghy and Farag, 2012; Huber et al., 2006). About 400 tons of carbon dioxide is produced from an average 500 MW power plant (Elmoraghy and Farag, 2012).

Another way of decreasing the cost of production of algae would be to develop a low-cost harvesting process (Huber et al., 2006). Two other key nutrients which are needed for growing algae are phosphorus and nitrogen, if there is a lack of these two nutrients it will slow down the growth of the algae (Elmoraghy and Farag, 2012). Yet another way in bringing down the cost of the algae production is if the algae grow directly in water where high amounts of phosphorus and nitrogen are found naturally (Elmoraghy and Farag, 2012).

Due to the algae being dependent on photosynthesis, where direct sunlight is needed, they cannot be grown on top of each other (Savage, 2011). If the layer of algae is greater than a few centimeters thick the sunlight will not reach the algae in the lower layer and these algae will die (Savage, 2011). To be able to grow a high number of algae for the production of biofuel a large area of open surface of water is needed which is another problem when producing fuels based on algae oil (Savage, 2011).

The algae used in making biofuel are single cell algae that produce proteins, lipids and carbohydrates from carbon dioxide, hydrogen and nitrogen (Savage, 2011). The extraction of their oil is done by breaking the cells open and this oil can then be converted into hydrocarbon-based fuel (Savage 2011).

The high water content (80-90 % of the content is from water) means that the algae needs to be pretreated to reduce the content of water (Elmoraghy and Farag, 2012; Patil, 2008). These pretreatments are harvesting and dewatering (Elmoraghy and Farag, 2012; Patil, 2008). Some of the harvesting methods are centrifugation and drying the algae into large dry
flakes (Elmoraghy and Farag, 2012; Patil 2008). However, another possibility is using direct hydrothermal liquefaction; this method is able to directly convert the wet biomass into fuels without the steps of reducing the water content (Aresta et al., 2005; Minowa et al., 1995; Patil, 2008). Biomass liquefaction is the process where the oxygen content of the biomass is removed and this can be done to some biomass including algae (Aresta et al., 2005; Minowa et al., 1995; Patil, 2008). The removal of the oxygen will give a higher heating value which leads to more hydrocarbon like contents of the product (Patil, 2008). Figure 2 shows a simplified version of the algae oil based jet fuel production process.

The oils generated from this process have a viscosity which is ten or even more times greater than the viscosity of jet fuel (Elmoraghy and Farag, 2012). The high viscosity unfortunately leads to the filters in modern day airplane engines clogging up causing excessive damage to the engine (Elmoraghy and Farag, 2012). However, there is a way to reduce the viscosity of the algae oils through transesterification (Elmoraghy and Farag, 2012).

The biomass from the algae that is left after the oil extraction can be used as a protein source for cattle and can even be fermented into alcohol (Elmoraghy and Farag, 2012; Patil, 2008).

Even though the production of biodiesel from algae is water costly this method leaves a smaller water footprint than other types of biodiesel.
production feedstock, see Table 3 (Elmoraghy and Farag, 2012). The water footprint is a measurement of how much fresh water that is needed to produce the biomass which we use, the water footprint can also measure how much water is used to produce other goods we use such as clothing or the food we eat (Hoekstra et al., 2011). The water footprint can be significantly decreased if the method of growing algae in wastewater or seawater is perfected (Elmoraghy and Farag, 2012; Kinder and Rahms, 2009). There are a lot of investments worldwide in the production of algae (Su et al., 2017). These investments seem to be mainly focused on the process of making the production of algae cheaper and in finding the best suitable species of algae which produces the highest yield of oil (Su et al., 2017).

Table 3. The amount of water used, in liters, in production of 4 l biodiesel from three types of different plant oils; soybean, canola and algae (Elmoraghy and Farag, 2012).

<table>
<thead>
<tr>
<th>Types of feedstock</th>
<th>Water mount in liters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soybean</td>
<td>59052</td>
</tr>
<tr>
<td>Canola</td>
<td>21993</td>
</tr>
<tr>
<td>Algae</td>
<td>1136-3784</td>
</tr>
</tbody>
</table>

6.2 Lignin

Lignocellulose is composed of cellulose, hemicellulose and lignin (Zaldivar et al., 2001). Lignin is a biomass which is rich in aromatic benzene rings and could theoretically be used in bio-jet fuels (Cheng and Brewer, 2017). As described in section 4, alkyln-benzenes with a low molecular weight are desirable because they cause less soot combustion than other types of aromatics (Cheng and Brewer, 2017). The fact that they are able to be produced from lignin makes lignin into a desirable jet fuel base (Cheng and Brewer, 2017). However, there are some challenges with using lignin as a base in a bio-jet fuel due to the complexity of the feedstock (Wu et al., 2017). It is believed that lignin derived biofuel cannot be utilized directly as transportation fuel, because it has a high oxygen content, acidity and is instable, and has a high viscosity (Wu et al., 2017). However, there has been a different approach on deriving jet fuel from lignin and it showed that it is possible to derive C8-C15 hydrocarbons and aromatics, two important components in jet fuel, meaning that lignin meets the same requirements as current day jet fuel (Bi et al., 2015).

The transformation from biomass into the hydrocarbons needed for jet fuel is done in three steps (Bi et al., 2015). First the lignin has to be cracked to
become low-carbon aromatic monomers, this is done by a catalytic cracking of the lignin (Bi et al., 2015). The catalytic cracking of the lignin is done at high temperatures, however a temperature over 500 °C leads to a second cracking which is not favorable for the production of the hydrocarbons, because the range would be too low for jet fuel (Bi et al., 2015). In the second step the aromatic monomers has to be alkylated; this is done to produce C8-C15 aromatics (Bi et al., 2015). This step can be completed at low temperatures, it can even be done in room temperature, 20 °C (Bi et al., 2015). However, the process seems to favor a slightly higher temperature to produce the aromatics in the desirable length, there are indications that 60 °C is the best temperature for this process (Bi et al., 2015). The final step is done to produce C8-C15 hydrocarbons which are needed in jet fuel, and is done by hydrogenation of the C8-C15 aromatics (Bi et al., 2015). This step is temperature dependent, it has been shown that when hydrogenating C8-C15 aromatics at 90 °C the conversion of the aromatics was only about 20% (Bi et al., 2015). However, when increasing the temperature to 180 °C it also improved the hydrogenation efficiency (Bi et al., 2015). When preforming the last step at this temperature nearly all of the C8-C15 aromatics had been converted to the desired cyclic alkanes (Bi et al., 2015).

As shown in Table 4 the two lignin derived products, aromatic biofuel and cyclic alkane biofuel, meet the specifications of the other jet fuels shown in Table 2. The findings indicate that from lignin the C8-C15 aromatics and cyclic alkanes can be reached in the range of jet fuel (Bi et al., 2015).
Table 4. Table over Bi et al., work and the specifications of the two different fuels produced; Aromatic biofuel (ABF) and cyclic alkane biofuel (CBAF) (Bi et al., 2015). Some components are undetected, meaning that no trace of these components were found (Bi et al., 2015).

<table>
<thead>
<tr>
<th>Specifications</th>
<th>ABF</th>
<th>CBAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat of combustion (MJ/kg)</td>
<td>42.5 ± 1.0</td>
<td>45.9 ± 0.8</td>
</tr>
<tr>
<td>Freezing point (°C)</td>
<td>≤ 70</td>
<td>≤ 70</td>
</tr>
<tr>
<td>Kinetic viscosity at -20 °C (mm²/s)</td>
<td>6.22 ± 0.28</td>
<td>7.46 ± 0.31</td>
</tr>
<tr>
<td>Hydrogen content (wt.%)</td>
<td>10.4 ± 0.5</td>
<td>14.2 ± 0.7</td>
</tr>
<tr>
<td>Total oxygen (wt.%)</td>
<td>0.096 ± 0.007</td>
<td>undetected</td>
</tr>
<tr>
<td>Total sulfur (wt.%)</td>
<td>undetected</td>
<td>undetected</td>
</tr>
<tr>
<td>H/C (mol ratio)</td>
<td>1.40 ± 0.07</td>
<td>1.98± 0.11</td>
</tr>
</tbody>
</table>

6.2.1 Fungi

As mentioned in section 6.2 the biomass from lignocellulose is attractive as a renewable fuel source (Cheng and Brewer, 2017; Wu et al., 2017) This is mainly due to the large availability of the biomass, the low cost of the production of lignin and the aromatic compounds of the biomass (Cheng and Brewer, 2017; Wu et al., 2017). However, there is a problem with the availability of a low-cost way to produce jet fuels from a lignin base, due to the complexity of the biomass (Wu et al., 2017).

Wu and his colleagues did an experiment in 2017 to look at four endophytes and their consolidated bioprocessing potential (CBP), these characteristics have the potential to convert lignocellulosic biomass to biofuels (Wu et al., 2017). All the endophytes are rich in carbohydrate active enzymes, fungal oxidative lignin enzymes and terpene synthases; this was found through a genomic analysis (Wu et al., 2017). They found monoterpenes and sesquiterpenes, they are similar to the hydrocarbons found in petroleum base jet fuels (Edwards et al., 2010; Harvey et al., 2010; Wu et al., 2017) The monoterpenes and sesquiterpenes contains close to zero oxygen content and they have high density which makes them important compounds, indicating that this type of chemical compound could work in drop in fuels for aviation fuel (Wu et al., 2017). Drop in fuels means that there is no need for any new equipment, the new fuel can be used in the systems used today (Air Transportation Action Group, 2012). After cellulase activity assays they found that the endophytes have the ability to breakdown the lignocellulosic feedstock directly because the endophytes secrete cellulase (Wu et al., 2017). By
being able to breakdown the feedstock directly, less steps are needed making the whole process cheaper and making it more plausible for usage (Wu et al., 2017).

6.3 Camelina

The interest in growing camelina is from the need of oilseed crops for the transportation industry which do not have a food use (Shonnard et al., 2010). Camelina is a plant which its oil can be used in BIO-SPK process (Moser, 2010; Shonnard et al., 2010). Camelina growth season is 85-100 days which is a short season (Moser, 2010; Shonnard et al., 2010). It is a plant that is well adapted to different sort of stress such us cold and drought (Moser, 2010; Shonnard et al., 2010). It can germinate at low temperatures and is frost tolerant which makes it a crop that can grow during winter seasons (Moser, 2010; Shonnard et al., 2010). However, it has a lower tolerance for rain than other oilseed crops (Moser, 2010; Shonnard et al., 2010).

The camelina crops are grown in the same area as wheat (Moser, 2010; Shonnard et al., 2010). This might indicate that the growing of camelina will deprive growth area for wheat (Moser, 2010; Shonnard et al., 2010). However, the growing grounds can be rotated which would indicate that every other or every third year camelina can be grown (Moser, 2010; Shonnard et al., 2010). Having the ground rotated has shown to benefit the wheat crop (Moser, 2010; Shonnard et al., 2010). The moisture of the soil will increase which would increase the crop yields the next year (Shonnard et al., 2010). Not growing the same crops every year and breaking the crop cycle will reduce pest problems and the crops will be less accessible to diseases (Shonnard et al., 2010). The camelina has shallow roots which make them drought resistant and these shallow roots would keep the nutrients in the soil at the same quantitive as before the camelina season (Shonnard et al., 2010). The fact that growing camelina favors other crops, from the rotation of the soil, it will not be any loss in food producing land (Shonnard et al., 2010).

In the U.S. it is suggested that more than five million acres can potentially grow camelina which will not have a negative impact on the food supply (Shonnard et al., 2010). This amount of growing area could produce 800
million gallons of oil each year for the usage in biofuel. (Shonnard et al., 2010)

BIO-SPK fuel from rotation crops has been estimated at a cost of $3.70 per gallon which is only 60 cents more than commercially used jet fuels used today (Reimer and Zheng, 2016). The U.S. Air Force has done a few test flights on a blend of camelina based jet and JP-8 jet fuel. These test flights where all successful not showing any complications (Moser, 2010).

6.4 Rapeseed

Rape is a plant that produce oil, the plant has small dark seeds and these seeds has an oil content of 40-50 % (Bernesson, 2004). The rapeseed oil is an oil that can be used in the BIO-SPK process. One acre of rape produces ten times less oil than one acre of algae (Naumienko and Rarata, 2010). However, the biomass from rape which is left after the oil extraction can be a protein source for cattle (Arvidsson et al., 2011).

During the spring of 2017, SAAB conducted a series of test flights with their Gripen (SAAB, 2017). The fuel powering the plane was CHCJ-5 which is a 100% bio-jet fuel made from rapeseed oil (SAAB, 2017). The test went without any complications showing that it is possible for a one engine plane to be driven by alternative fuel (SAAB, 2017). Being able to power a flight from 100% renewable fuel takes away the dependents of importing different kinds of fuel (SAAB, 2017). The rapeseed oil based fuel can be produced and used in the same country which will save the transportation costs and might also be important in the future for defense purposes (SAAB, 2017).

6.5 Jatropha

Jatropha is an oil seed bearing plant which is grown in subtropical and tropical countries (Zhang et al., 2013; meyer). The plant has a rapid growth, high oil content and drought tolerance (Zhang et al., 2013).

The oil rich fruit from the Jatropha plant can be used as a base in BIO-SPK (Zhang et al., 2013; Arvidsson et al., 2011; Rahmes et al., 2009). To reduce the water content of the fruit they are placed in sunlight (Arvidsson et al.,
However, the biomass left from the oil extraction can not be used as protein sources for cattle due to that it is toxic to animals (Meyer et al., 2012; Arvidsson et al., 2011). Due to that the Jatropha is toxic, humans have not been growing the plant for that long which indicates the plant has not been fully explored (Meyer et al., 2012).

6.6 Switchgrass

Switchgrass is a type of grass which does not need a lot of water, fertilizers and land to be able to grow (Payan et al., 2014). It is the lignin in this biomass which can be fermented into alcohol and then transformed into bio-jet fuel (Payan et al., 2014).

If a flight powered from jet fuel made from switchgrass the carbon dioxide emissions would be lowered to about 63% compared with petroleum based flights (Payan et al., 2014). A flight powered by a 50/50 blend of switchgrass based and petroleum based fuel the carbon dioxide emissions would be lowered to about 13% (Payan et al., 2014).

7 Costs

Even if bio-jet fuels have the ability to lower emissions of greenhouse gases it will not be used by airlines if there is no financial gain (Air Transportation Action Group, 2012; Hileman and Stratton, 2014). Biofuels for aviation use currently are very rare and comparatively expensive, it is theorized that with a higher amount of bio-jet fuel products coming onto the market the prices of biofuels for aviation will most probably decrease (Air Transportation Action Group, 2012). For the aviation industry to realistically be willing to use bio-jet fuels the costs will have to meet the costs of the fossil based fuel used today (Air Transportation Action Group, 2012). The cost of traditional jet fuel will become more expensive over time, due to tax costs of carbon dioxide emission (Air Transportation Action Group, 2012). It is supposed that the cost of carbon dioxide emission will double the cost of fossil fuel by the year 2050 (Air Transportation Action Group, 2012).

To be able to keep the cost as low as possible renewable jet fuel must be close to identical to jet fuel that is already used in plane engines (Air
Transportation Action Group, 2012). If this requirement is met it will mean that no new engines or planes would be needed and designing a new fuel delivery system will not be necessary (Air Transportation Action Group, 2012). Basically, no extra requirements for any airports would be needed (Air Transportation Action Group, 2012). The renewable fuels also have a large production potential meaning that this type of fuel will be able to compete with the petroleum based fuels that are used today (Hileman and Stratton, 2014). However, a lot of water is needed for the production of petroleum, water that could be used for producing edible feedstock (Hileman and Stratton, 2014). This is however also a problem when creating fuel from biomass (Hileman and Stratton, 2014). The production of biomass based fuels requires a lot of water when producing the biomass (Air Transportation Action Group, 2012). That is why, when producing a biomass based fuel for the aviation industry, the focus is finding a base which has a low impact on feedstock and water usage (Air Transportation Action Group, 2012).

There are some main theories in how a change in the aviation industry can occur, with lowering of the carbon dioxide emission (Hileman and Stratton, 2014). The first theory of how to change the aviation industry is to increase the cost in usage of fossil fuels, a strategy which has to be done through government climate policies (Hileman and Stratton, 2014). The overall production cost of the production of jet fuel made from biomass must decrease as well to theoretically be able to use bio-jet fuels in the aviation industry. (Hileman and Stratton, 2014). However, it looks like the economics and the policies surrounding petroleum based fuels are going in the direction where there will be an increase in the price of the usage of these types of fuels (Hileman and Stratton, 2014).

### 7.1 Flights Powered by Bio-Jet Fuel

There have been multiple test flights done with different types of bio-jet fuels (Kinder and Rahmes, 2009; Moser, 2010; Air Transportation Action Group, 2012; EcoSeed, 2012; SAAB, 2017; Yao et al., 2017). Over 1500 passenger flights have also been flown on bio-jet fuel blends (Air Transportation Action Group, 2012). From the advances already made from bio-jet fuels a few targets have been set up (Air Transportation Action Group, 2012). Two of these targets are: 1.5% improvement of military fuel efficiency per year until 2020 and to halve the carbon dioxide emissions from 2005 by 2050 (Transportation Action Group, 2012). Due to the results
from all the different flights powered by bio-jet fuel these targets seem to be reachable (Air Transportation Action Group, 2012).

8 Discussion

The biomass which could be produced for jet fuel could also be used for ground transportation, energy, and other heat sources (Hileman and Stratton, 2014). One example is that treated cellulosic biomass could be used directly in power plants which would produce energy and heat, which gives a large competition for renewable energy resources (Hileman and Stratton, 2014). However, energy and heat we can get from different energy sources such as wind power and solar energy, cannot be used for the powering of commercial planes (Air Transportation Action Group, 2012). Since the production of heat and energy can be found at other power sources, I believe that it is important to use the biomass which can be used for aviation fuel for that purpose to help with the lowering of the greenhouse gas emissions from the aviation industry.

The use of advanced biofuels instead of first generation biofuels would probably lower the usage of edible feedstock. Thus, the aviation industry will not be depriving the world of the food it needs.

Some genetic modifications to the different biomasses would probably help with the costly situation that the bio-jet fuels are in today. To genetically alter all of the different plants used in BIO-SPK to produce more oil would probably lower the amount of plants needed and the growth area would become smaller. A different way of lowering the cost of the production of bio-jet fuel from algae could be to genetically alter the algae to produce shorter fatty acids. This would eliminate the need for hydrocracking the longer chains, which would lower the cost of the production.

More knowledge towards the jatropha plant would probably give a better growth rate. To genetically alter the plant height, earlier maturity, which would shorten generation times, and to increase resistance towards pests and diseases would probably give more fruit and a higher oil yield.

I also believe that more investments are needed in trying to understand and develop the CBP systems in fungi. This will simplify and make the process of getting jet fuels from lignin easier, quicker and probably cheaper.

To summarize how to get the advanced jet fuels on the market a simplification of the production should be found, and a minimization of
steps of the different processes. This would probably make the process cheaper which gives the fuels a possibility to compete with the fuels that are on the market today.

In the future, there is a possibility that there would be a decrease in demand of sources of high energy density fuels because ground transportation can be powered by electricity (Air Transportation Action Group, 2012). Because of the high energy demand for safe transportation for aviation transport this industry cannot be powered by electricity (Hileman and Stratton, 2014). This indicates that more time and money will have to be invested in bio-jet fuels.

Getting 100 % advanced bio-jet fuels on the market might not happen tomorrow but the knowledge and production of them are improving quickly. I believe that it can be done, SAAB already showed that it can be done by using rapeseed oil and test flights using jet fuel from algae oil or from lignin will probably soon follow.

8.1 Social and Ethical Aspects

The aviation industry has grown rapidly and the carbon dioxide emissions have grown as well (Jiménes-Díaz et al., 2017). There are no indications that the aviation industry will stop growing and within the next 20 years the commercial aviation industry is expected to grow 4.8 % (Boeing, 2016). The carbon dioxide emissions will probably grow as well in the same manner. Fuels made from biomass does not have as big of a negative impact on the emissions of carbon dioxide (Gronenberg et al., 2013; Liew et al., 2016). The petroleum prices are set to increase as well probably making air transportation more expensive for their passengers (Hileman and Stratton, 2014). In order to keep the emissions down a new energy source needs to be found, and the advanced bio-jet fuels are the ideal fuels to take over from the petroleum based fuels (Air Transportation Action Group, 2012).

Fuels made from first generation biomass have a negative impact on our society due to the increasing food prices, high water usage and pollution (Air Transportation Action Group, 2012; Daroch et al., 2013; Fairley, 2011). Producing bio-jet fuels from nonedible feedstock would keep the food prices and pollution down, having a less negative impact on our society (Balan, 2014; Hileman and Stratton, 2014). The overall water usage
for the production of advanced biofuels is also smaller than the usage for first generation biofuels (Elmoraghy and Farag, 2012).

Using food that people around the world can eat for the production of first generation bio-jet fuels might not be ethically right but using advanced biofuels will not deprive the people of their food sources. The advanced bio-jet fuels could also have a positive impact on the military aviation (Dagaut, 2005). Advanced bio-jet fuels produce less soot emissions, making the military planes harder to detect on the radar (Dagaut, 2005). Improving the military might not be ethically correct but I believe that an overall improvement on the aviation industry, whatever it is, will probably always also benefit the military industry.

9 Acknowledgment

I would like to thank my supervisor professor Johan Edqvist for supporting and helping me in my work. I would also like to thank Alexander Blochel for helping with the structure of this thesis.
10 References


