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Aviation Fuels and Peak Oil

Emma Nygren

UPPSALA UNIVERSITET

Teknisk- naturvetenskaplig fakultet
UTH-enheten

Besöksadress:
Ångströmlaboratoriet
Lägerhyddsvägen 1
Hus 4, Plan 0

Postadress:
Box 536
751 21 Uppsala

Telefon:
018 - 471 30 03

Telefax:
018 - 471 30 00

Hemsida:
http://www.teknat.uu.se/student

Abstract

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In this thesis future aviation fuel supply is compared to future aviation fuel demand. Most aviation fuels are jet fuels originating from crude oil. The crude oil must be refined to be useful and jet fuel is only one of many products that can be derived from crude oil. Jet fuel is extracted from the middle distillates fraction and competes, for example, with the production of diesel.

Crude oil is a limited natural resource subject to depletion and several reports indicate that the world's crude oil production is close to the maximum level and that it will start to decrease after reaching this maxima. On the other hand, it is predicted by the aviation industry that aviation traffic will keep on increasing.

The industry has put up ambitious goals to increase fuel efficiency of the aviation fleet through better engines, better flying routes and better aerodynamics, but still the demand for aviation fuel would grow. Traffic is predicted to grow by 5 per cent per year to 2026, fuel demand by about 3 per cent per year. At the same time aviation fuel production is predicted to decrease by several per cent a year after the crude oil production peak is reached. This scenario envisages a substantial lack of jet fuel by the year 2026. The aviation industry will have a hard time replacing this with fuel from other sources even if air traffic remains at today's level.

Handledare: Kjell Aleklett
Ämnesgranskare: Allan Hallgren
Examinator: Ulla Tengblad
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Svensk sammanfattning

Världens flygtrafik har ökat stadigt, sedan 1970 har antalet passagerarkilometer ökat med 4,9 procent per år. Passagerarkilometer (RPK) är antalet betalande passagerare multiplicerat med den sträcka som flygs och är ett vanligt mått inom flygbranschen. Flygindustrin ser ljust på framtiden och tror på en fortsatt trafikökning, både Airbus och Boeing förutspår att antalet RPK kommer att fortsätta att växa med runt 5 procent per år till och med 2026.

Trafikökningen leder till att även efterfrågan på flygbränsle kommer att stiga. Till skillnad från bilindustrin har dock flygindustrin kontinuerligt arbetat för att minska bränslekonsumtionen. Sedan 1960-talet har konsumtionen per RPK gått ner med 70 procent, det innebär att trafik och bränslekonsumtion inte är helt ihopkopplade. Målet för framtiden är att minska bränslekonsumtionen med 50 procent till 2020 genom att effektivisera motorer, förbättra aerodynamik och planering av flygrutter.

Det har gjorts många råoljeproduktionsprognoser, det finns prognoser som visar att produktionen kan växa fram till 2030 och det finns prognoser som visar att den maximala produktionsnivån är nådd, eller snart kommer att vara nådd. Det är den senare typen av prognos som har används i den här rapporten. Olja hittas i allt mindre utsträckning och den olja som hittas är oftast av sämre kvalitet och finns på platser som gör produktionen dyr. Prognoser som studerats är *Giant Oil Fields* av *Fredrik Robelius* och *Crude Oil- The Supply Outlook* av *Energy Watch Group*.

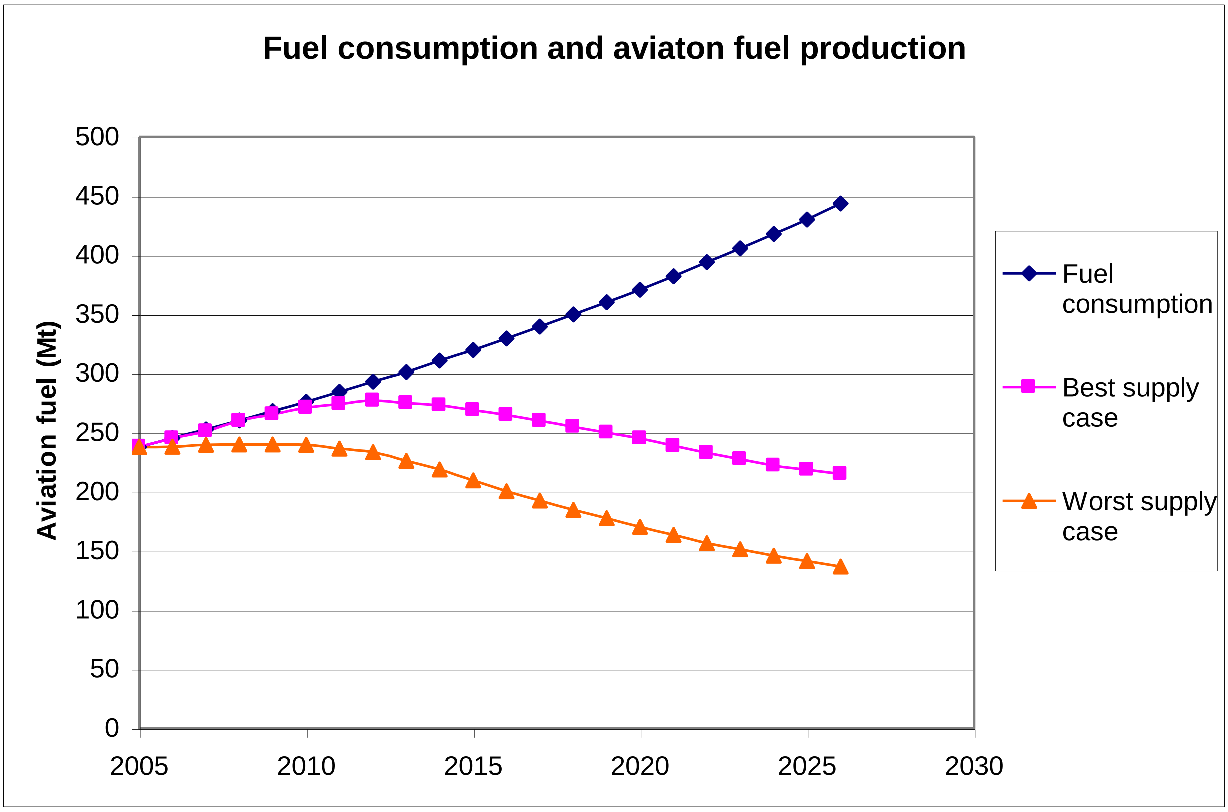
Råolja är en komplex samling av ett stort antal molekyler. Huvudkomponenterna är kol och väte, oftast finns svavel, kväve, syre och metaller i väldigt små mängder. För att råoljan ska vara användbar måste den raffineras. Uppbyggnaden av raffinaderiet ser lite olika ut beroende på den råolja som används och vilka produkter som är önskade. Ju tyngre oljan är och ju fler icke-kolväten som den innehåller desto mer krävs för att få ut högvärdiga produkter. Sådana produkter är i huvudsak fordonsbränslen, men även råvara till annan industri som till exempel plastindustrin. De viktigaste bränslena är bensin, diesel, flygfotogen och eldningsolja. Flygfotogen och diesel är liknande produkter och fotogenet kan användas till att späda ut diesel. Andelen flygfotogen skulle kunna öka, men på bekostnad av andra bränslen, främst diesel. Dieseln är väldigt viktig inom jordbrukssektorn och för lastbilstransporter.

Den framtida efterfrågan på flygbränsle har i denna rapport räknats ut med data för trafik och bränsleförbrukning som grund. Resultatet blev att efterfrågan förutspås växa med omkring 3 procent per år, beroende av hur effektiviseringsmålen kommer att uppnås. År 2005 var andelen flygbränslen 6,3 procent av världens raffinaderiproduktion, vilket motsvarade 238 miljoner ton. Prognoserna för oljeproduktion har räknats om till flygbränsle genom att flygbränslets andel har antagits vara konstant 6,3 procent av oljeproduktionen. Prognosen för efterfrågan av flygbränsle har sedan jämförts med prognosen för tillgång på flygbränsle fram till 2026.

Resultatet av en av de beräkningar som gjorts i examensarbetet visas i *Figur 1*. Gapet mellan efterfrågan och utbud kommer att vara mycket stort under förutsättning att flygbränslet förblir 6,3 procent av råoljeproduktionen och att trafiken fortsätter att växa med 5 procent om året.

Fortsatt trafiktillväxt kommer att vara svår att uppnå när oljeproduktionen minskar om det inte finns alternativa bränslen tillgängliga som skulle kunna minska gapet nämnvärt i den närmaste framtiden. Det pågår utveckling av biobränslen men det kommer att ta tid, det är också oklart om det går att producera de stora mängder som krävs. Ett alternativt flygbränsle som används idag är syntetiskt bränsle från kol. Det tar dock tid att bygga ut en sådan industri och det motverkar samtidigt målet om att minska koldioxidutsläppen.

Slutsatsen är att det kommer att bli svårt att försörja världens flygplan med bränsle när råoljeproduktionen når sin maximala nivå och sedan minskar.



Figur 1: Framtida flygbränsleproduktion baserat på framtida trafik och flygflottans medelförbrukning, jämfört med flygbränsleproduktionen om råoljan följer produktionsnivån i bästa respektive sämsta scenariot i Robelius prognos. Källa: SIKA 2008, IEA 2007, Airbus 2007 och Robelius 2007.

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1 Introduction

The world's transport system is highly oil dependent and aviation is no exception, it can actually be counted as the most oil dependent transport. Annually more than 2 billion passengers enter an aeroplane to be transported to another city, country or continent. Transportation by air has its advantages primarily when travelling long distances and it makes it possible to connect the world and people in a completely different way than before. Aviation has made tourist trips to distant places possible. For example Thailand has become a very popular destination for Europeans, despite being a 12-hour flight away. Aviation has also made business connections easier and contributed to the growth of global economy.

This report will investigate the fuel component of the aviation business. Today almost 100 per cent of aviation fuel is extracted from crude oil, a fossil fuel subject to depletion. The characteristics of air travel mean that a lot of caution must be taken when introducing new fuels; being 10,000 meters in the air provides no room for failure and tests for approving aviation fuel are therefore rigorous.

Petroleum in the form of crude oil has been used for the past one hundred years in a steadily increasing amount. Most crude oil was found in the sixties and has been continuously extracted since. Eventually production will reach its maximum and start to decline. Many of the oil producing countries have reached that peak and their production is declining, for example the USA reached its maximum level in 1970 and Norway in 2003. Today more oil is consumed than found.

The availability of jet fuel can be one of the factors that will put constraints on the growth of the aviation industry. But there are a lot of things affecting the future of the aviation industry and the amount of available fuel for it. What is more important? Diesel for agricultural tractors or jet fuel for aviation? What will possible costumers choose? Airborne travel or travel by car? Will they be able to travel at all? Passenger traffic is dependent on the overall economic situation of a society; flying is mostly not essential to everyday life and vacation travel depends on people's economic situation and the price of the trip. What price are people willing to pay for a ticket?

1.1 Purpose

The purpose of this undergraduate diploma thesis is to investigate the production of aviation fuels and the supply and demand of it now and in to the future.

1.2 Method

Aviation fuels connect the different parts of this thesis: origin, production, usage, and consumption now and in the future. Aviation fuels are above all jet fuel used in aircraft with turbine engines, but a little part is also aviation gasoline used in small aeroplanes with piston engines.

The source of this fuel is, as mentioned, crude oil and therefore crude oil characteristics, classification, origin and production are investigated. Since crude oil is useless in its raw state the refining of it into useful products is also investigated and above all the refining of jet fuel.

Industry forecasts on future air traffic development are investigated to understand the aviation fuel demand in the future. Forecasts on future crude oil production are also investigated to get a picture of aviation fuel supply. Finally results in the form of future supply and demand of jet fuel are calculated.

To collect information, a literature study was done on refinery technology, crude oil characteristics, efficiency and construction of turbine engines and jet fuel characteristics. Information on air traffic development was sought on the Internet.

2 World aviation

Aviation is an important part of the transport system of today. This chapter will build a basis for creating a scenario of future aviation fuel demand by looking at the current state of the aviation industry and forecasts for air traffic development.

2.1 Current situation

Jet fuel is a petroleum product originating from crude oil and it is a part of global trade. The *World Oil Market Report* by the International Energy Agency (IEA) provides numbers on the amount of petroleum products consumed, for the countries in the Organisation for Economic Co-operation and Development (OECD), an organisation with 30 member states. Of a total demand of 49.19 million barrels of petroleum products per day in the OECD countries in 2007, 4.11 million barrels were jet fuel and kerosene, corresponding to 8 per cent of refined products (Figure 1). Demand is similar to consumption since there have been no major interruptions in supply.

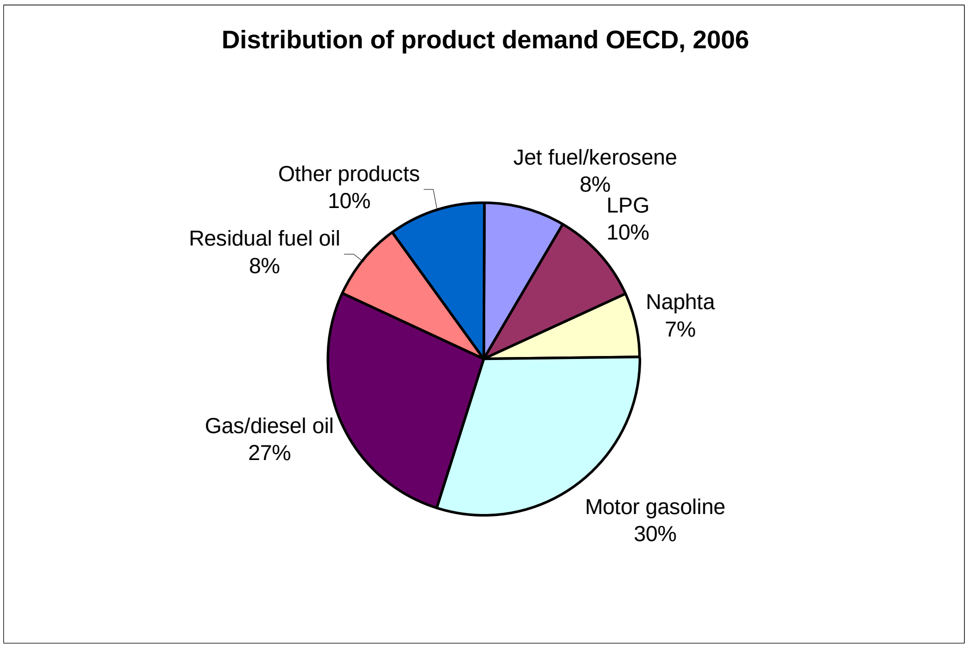

Figure 1: Demand for refined products in per cent. Source: Data from IEA 2008.

For the world, the numbers are somewhat different. The IEA has estimated the world's total refinery production in 2005 to be 3773 million tonnes (Mt). That part of production that is aviation fuel was 6.3 per cent (Figure 2), which corresponds to an aviation fuel production of 238 million tonnes, including both jet fuel and aviation gasoline.

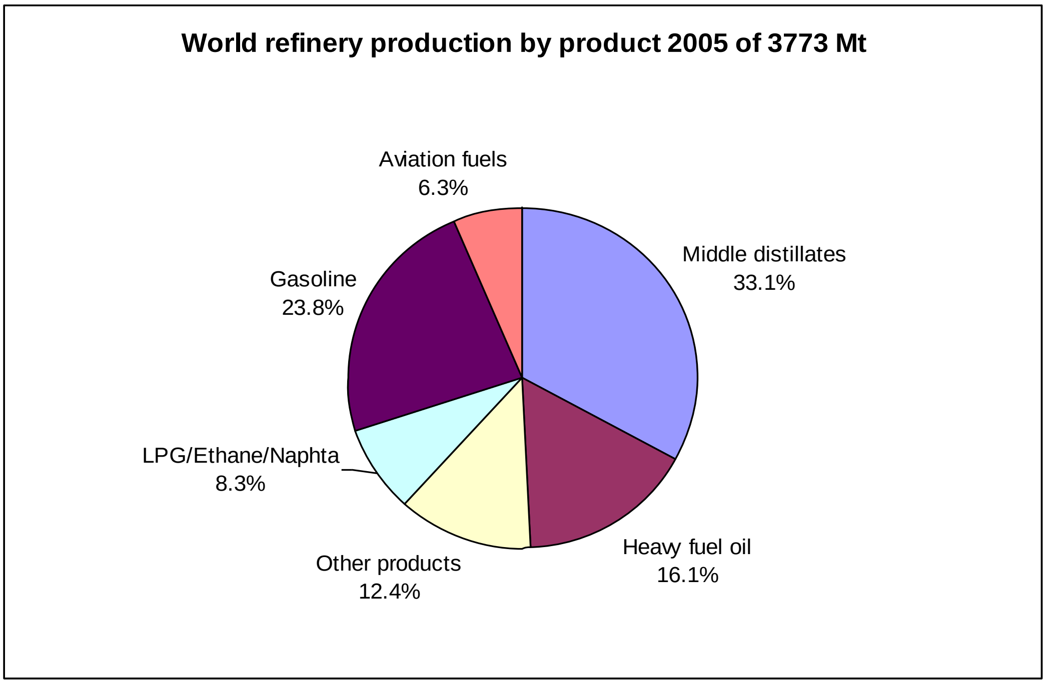

Figure 2: Distribution of manufactured products during 2005. Source: IEA 2007

2.1.1 Passenger traffic

The numbers of passengers carried have grown steadily, with few exceptions. Figure 3 shows the development of passenger numbers since the seventies for the member states of International Civil Aviation Organisation (ICAO). The increase in passengers corresponds to a 4.9 per cent growth per year from 1970 to 2006. In 2006 more than 2 billion people travelled by air.

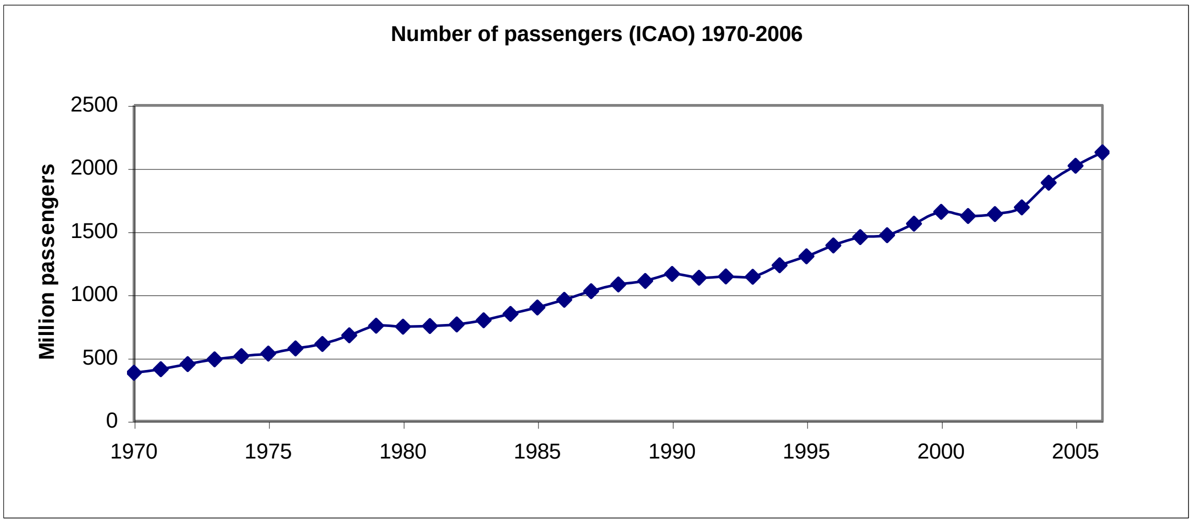

Figure 3: Number of passengers travelling with aircraft for ICAO member states. Source: Data from SIKA-institute 2008.

A common economic measure for aviation is Revenue Passenger Kilometres (RPK). It is the number of paying passengers times kilometres travelled. In 2005 3.7 trillion revenue passenger-kilometres were flown (SIKA-institute 2008). That corresponds to an average travel distance of about 1800 kilometres.

If the RPK numbers are divided by Available Seat Kilometres (ASK) the load factor is obtained, which is a measure of aircraft occupancy. The load factor has improved over the years as can be seen in Figure 4. It is easy to understand that a high load factor is crucial for efficient transportation.

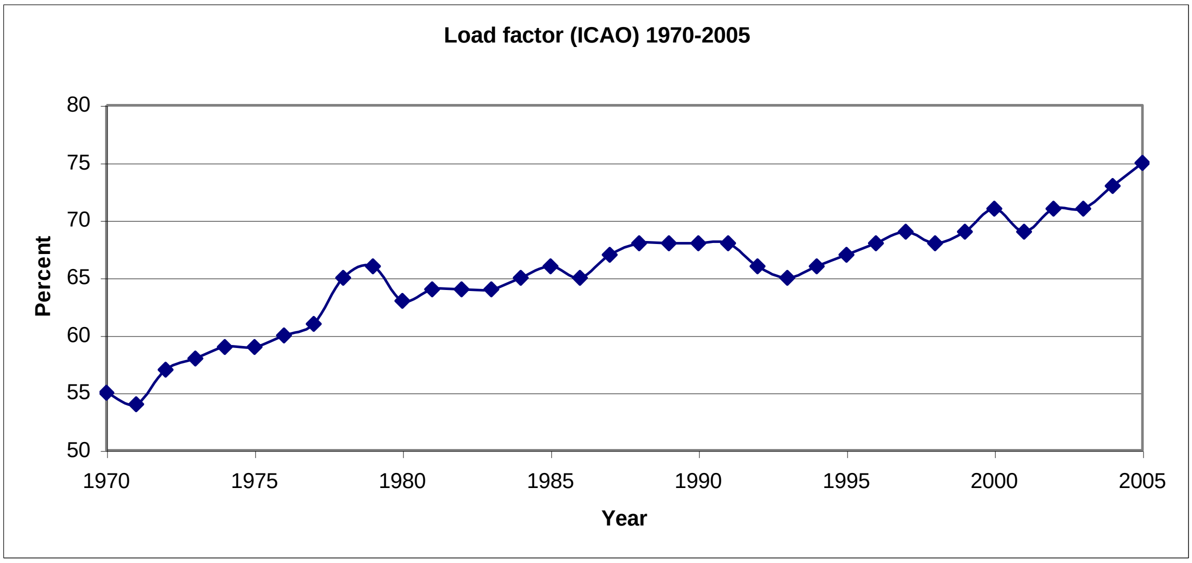

Figure 4: The change of load factor in ICAO member states. Source: Data from SIKA-institute 2008.

2.1.2 Goods traffic

The world fleet of aircraft does not only serve passenger transit, it also serves the transportation of goods. Goods suitable for air transportation are, for example, high value goods, spare parts for industry, perishable food items and other things that need fast transportation. The amount of goods transported by aviation has grown by 5.3 per cent per year since the seventies, going from 6.1 million tonnes to 37.7 million tonnes a year (SIKA-institute 2008). Every tonne is transported an average of 3780 kilometres. Counted in tonne-kilometres the growth since the seventies is 6.7 per cent per year. In value, 35 per cent of the inter-regional goods are transported by aeroplane (IATA (1) 2008). In tonne-kilometres, freight and mail are about 30 per cent of all scheduled revenue traffic (SIKA-institute 2008).

2.1.3 Military aviation

A third user of aircraft is the military. Military aircraft are different to civil aircraft and do to some extent require specialized fuels. More and more, military organizations such as NATO have left special fuels such as the wide-cut type of jet fuel. Kerosene, the type of fuel used by commercial traffic, is gaining in popularity. (Air BP 2000).

The Air Force represents about 10 per cent of aviation fuel use in the entire domestic market of the USA. However, it should be noted that the military is particularly large in the USA (The Wall Street Journal 2008).

2.2 Air transport forecasts

Many factors affect the future of aviation. For example, to be able to travel as a private person money and time are needed, and these two factors change with the state of the economy. Companies only send goods by air if it is cost effective and it is critical that fuel is available and not too expensive. Politics can also play a major role when it comes to demand for air travel, aviation is thought to be a big contributor to greenhouse gas emissions and there is a political desire to lower emissions. That may negatively affect the aviation industry.

Air transport forecasts built on market knowledge can be performed to get an idea of future air traffic demand. There are several organisations and companies that make these kinds of forecasts. Forecasters are for example Boeing, Airbus, the International Air Transport Association (IATA) and the Air Transport Association (ATA). Some of this data is available free of charge and some must be purchased.

In this thesis forecasts from Boeing and Airbus are compared.

2.2.1 Boeing forecast

Boeing is a United States company and one of the world's leading manufacturers of aircraft for civil and military use. Boeing manufactures 5 different types of aircraft from 100 to 500 passengers or for goods. Boeing also designs and manufactures systems for electronics and defence, rotorcraft, satellites, launch vehicles and advanced information and communication systems. Boeing is active all over the world and in terms of sales is a large exporter for the USA. (Boeing 2008)

The Boeing Current Market Outlook includes numbers for passenger growth, revenue passenger-kilometres growth, cargo growth and number of new aeroplanes in traffic. Table 1 one shows predicted market growth rate in some areas.

Table 1: Boeing Key Indicators, 2006 to 2026 (Boeing 2007)

	Market growth rate
Gross domestic product	3.1%
Number of passengers	4.5%
Revenue passenger-km	5.0%
Cargo traffic	6.1%

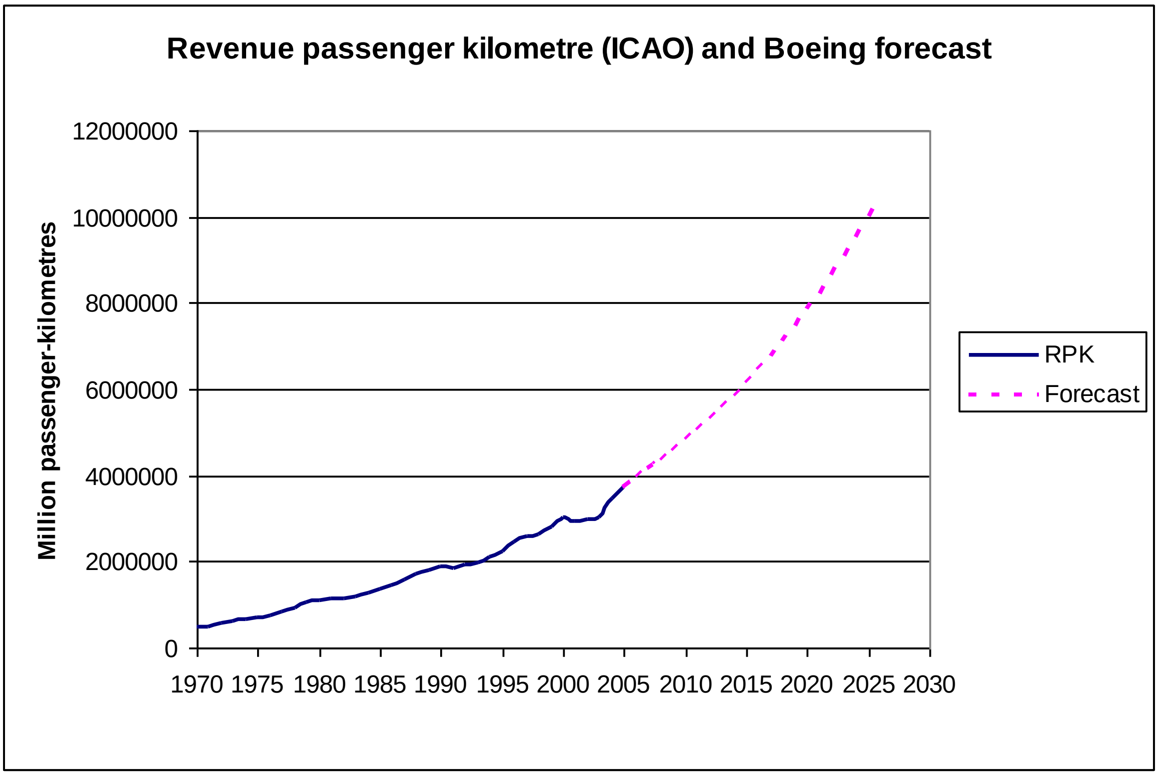

Figure 5: Real number for passenger-kilometres together with the forecast made by Boeing of 5 per cent growth in passenger-kilometres. Source: SIKA-institute 2008 and Boeing Current Market Outlook, 2007.

Figure 5 shows historical numbers for passenger-kilometres and predicted future development made by Boeing.

Boeing predicts that most of the rise in air traffic will be within, to, or from the Asia-Pacific region and that the increase of passengers carried will mostly be due to more people having the opportunity to travel. The Asia-Pacific region is forecast to be the new centre for air traffic.

Boeing also predicts that 80% of the aeroplanes flying today will be replaced by the year 2026 and that the new aircraft will be more fuel efficient and more comfortable.

Between 2007 and 2026 Boeing predicts that 28 900 new aircraft will be manufactured. Table 2 shows how the aeroplanes are thought to be divided by region.

Table 2: Total number of manufactured aircraft divided by region 2007-2026 (Boeing 2007)

Region	Number of aeroplanes	Per cent
Asia-Pacific	8350	29
North America	9140	32
Europe	6670	23
Middle East	1160	4
Latin America	1730	6
CIS	1060	4
Africa	490	2
Total	**28 900**	**100**

In 2006 the number of passengers was 2128 million (IATA), and with a growth rate of 4.5 per cent per annum there will be 5130 million passengers travelling by air by 2026.

2.2.2 Airbus forecast

Airbus is the other big aircraft manufacturer in the world, manufacturing jet aircraft from 100 seats up. Airbus is based in Toulouse, France and has 14 commercial aircraft models from 100 seats up to more than 500 seats. Airbus also manufactures military aircraft. The company exists all over the world, as do their costumers. Different parts are manufactured in for example U.K., Germany, Spain and France. The company was founded in 1970 to compete with the U.S dominance in the aviation industry and employs around 55 000 people today (Airbus 2008).

Airbus predicts that the number of Revenue Passenger-Kilometres will grow by 4.9 per cent a year by 2026, see Table 3. Freight traffic is predicted to grow by 5.8 per cent per year.

Table 3: Forecast for Revenue-Passenger-Kilometres growth 2007-2026 (Airbus 2007)

Passenger traffic growth in per cent	
Asia-Pacific	6.1
North America	3.5
Europe	4.5
Middle East	6.8
Latin America	5.7
CIS	5.6
Africa	5.3
The world	**4.9**

Airbus predicts that 95 per cent of today's aircraft will be recycled or replaced with more efficient aircraft by 2026, or, as they express it, with eco-efficient aircraft. Jet fuel consumption will therefore grow at a lower rate than passenger traffic. Table 4 shows how Airbus predicts that new aircraft are to be divided by region.

Table 4: Total number of manufactured aircraft divided by region 2007-2026 (Airbus 2007)

Demand by region	Number of aeroplanes	Per cent
Asia-Pacific	7231	30.9
North America	6257	26.8
Europe	5729	24.5
Middle East	1184	5.1
Latin America	1448	5.1
CIS	656	2.8
Africa	880	3.8
Total	**23 385**	**100**

The world's air traffic distribution profile is predicted to look a bit different in 2026 than that in 2006. Asia-Pacific will be the largest market instead of North America, and the Middle Eastern market, which shows the most rapid growth, grows from a low value and will by 2026 be the home region for 7 per cent of the world's airlines (Figure 6).

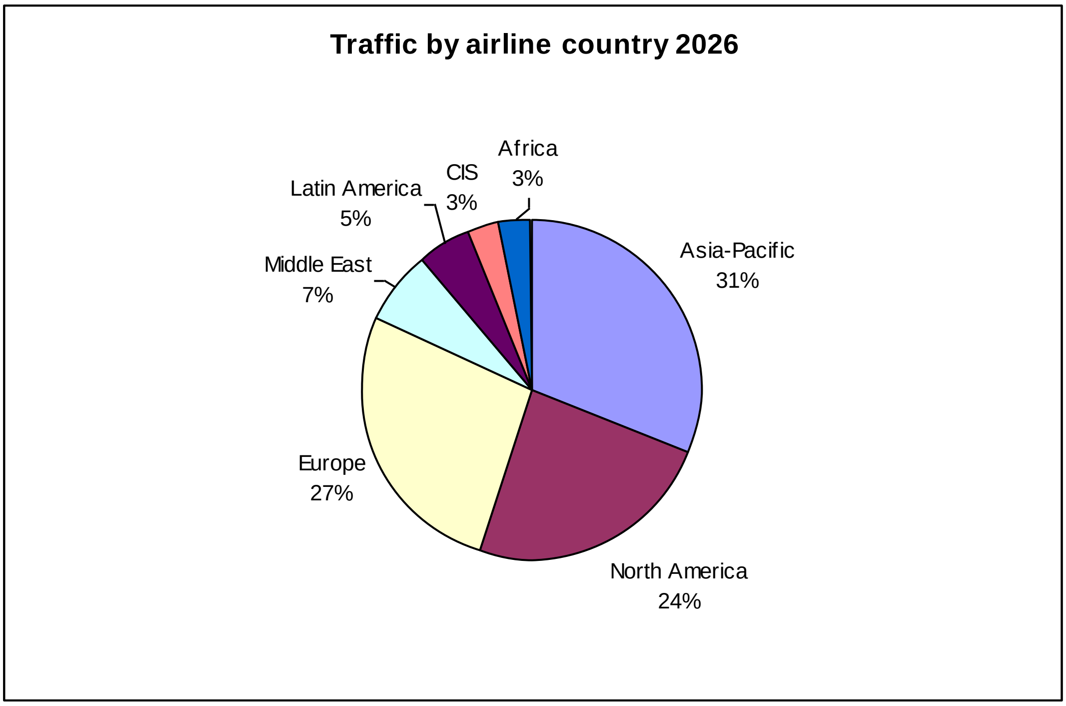

Figure 6: Predicted world aviation traffic divided by airline domicile year 2026. Source: Airbus Global Market Forecast 2007.

2.2.3 Comparing Boeing and Airbus forecasts

Boeing believes that the number of new aircraft will be greater, 28 600 compared to Airbus's 23 400. Both companies believe in a strong Asia-Pacific market but also that a lot of new aeroplanes will be sold to North America and Europe. The European and American markets will grow at a slower rate than the Asia-Pacific and some of the new aeroplanes will replace those being retired, whereas in Asia-Pacific a lot of new capacity will be added.

3 Future jet fuel demand

Future jet fuel demand is dependent on air traffic demand and fuel efficiency of the world's aviation fleet.

3.1 United States jet fuel forecast

The Energy Information Administration (EIA) is a section of the U.S. Department of Energy. EIA's mission is to provide statistics, data analysis on resources, supply, production and consumption for all energy sources. The EIA predicts a jet fuel consumption rise of 1.5% per year from 2006 to 2030 in the United States, going from 1.62 million barrels per day (Mbbl/day) in 2006 to 2.31 million barrels per day in 2030 (EIA 2008). That corresponds to 76 million tonnes in 2006 and 108 million tonnes in 2030 (Figure 7).

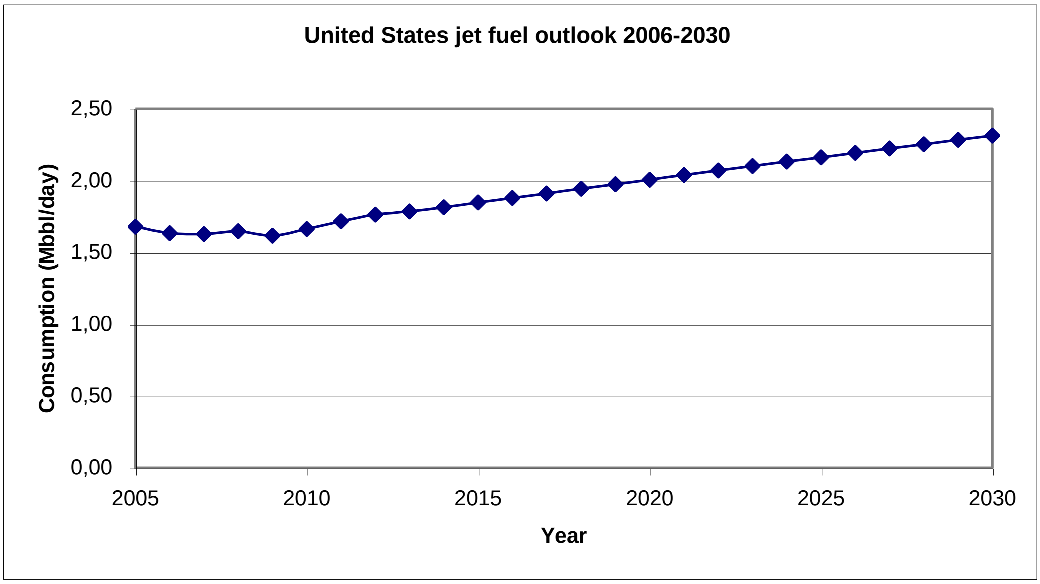

Figure 7: Forecast for United States jet fuel demand until 2030. Source: EIA 2008.

3.1.1 Comparing EIA and Airbus

In comparison with forecasts for passenger growth, it can be seen that the number of passengers globally, are forecast to grow at a much higher rate than jet fuel use in the USA. The Airbus number for traffic growth in North America is 3.5 per cent, which is to be compared to the EIA forecast of 1.5 per cent jet fuel consumption growth in the USA. A fuel efficiency increase of 2 per cent a year is necessary if both forecast should be true. It is a smaller efficiency increase than the industry's stated goal of about 4 per cent a year (see Table 7).

3.2 Jet fuel consumption and traffic growth

Jet fuel demand and aviation traffic growth are not strictly correlated since the efficiency of aircraft and air traffic management are continually improving. The airlines and the aeroplane manufacturers keep improving the planning and routing of traffic and keep improving the fuel efficiency of aeroplanes to meet the goal of less jet fuel consumption. The aviation industry has actually gone through huge development since the first commercial aircraft came in to service. Since the 1960s aircraft are 75 per cent quieter and have reduced fuel consumption by 70 per cent (Airbus 2007). Today average fuel consumption is less than 5 litres/100 RPK. Modern aircraft consume about 3.5 litres/100 RPK (AEA 2008).

Industry and politicians in Europe have put up a goal to improve the fuel efficiency by 50 per cent per RPK before the year 2020 (ACARE 2001). That is a very ambitious goal and it is meant to be, placing pressure on manufacturers, airlines and countries. The goal is supposed to be met through replacement of old aircraft with new, which are more fuel efficient combined with better routing and planning of air traffic. The aircraft manufacturers are supposed to contribute 20-25 per cent, the engine manufacturers 15-20 per cent and improved operations 5-10 per cent (Airbus 2007).

3.3 Aviation and economy

The demand for air travel is related to the state of the economy, often measured by the Gross Domestic Product (GDP). Generally the demand for air travel grows in good economic times and vice versa in the bad times. GDP and the aviation industry are also internally connected since aviation contributes to the economy. The aviation industry stresses the importance of aviation traffic to economic development throughout the world. The aviation industry’s part of global GDP is 2.4 per cent according to the Air Transport Action Group (ATAG 2005), taking in to account direct, indirect and induced impacts. In the USA aviation is thought to consume less than 3 per cent of total energy, but to contribute to about 6 per cent of the gross economic output and drive almost 9 per cent of national employment (FAA 2008).

The cost for fuel is now an average of 30 per cent of total airline expenses (IATA 2007). That makes fuel the airline companies’ largest single expense. During the spring and summer (2008) the cost that corresponds to fuel has grown even more and for some companies it has become as much as 50 per cent of total costs.

Taxes on fuel are not common in the aviation industry, instead airlines pay user charges for infrastructure such as airports and navigation. Charges that finance the whole infrastructure needed for air transport, according to ATAG. In Sweden LFV operates and develops state owned airports (all major airports). The charges paid by airlines are due to aircraft emissions and noise, number of passengers, take-off weight and current departing airport with an internationally decided navigation fee (LFV(1) 2008). LFV have a price policy to lower charges when yield specifications are fulfilled which have lead to a decrease of passenger charges for international traffic as of the first of April 2008, possible due to an increase in passengers (LFV(2) 2008).

4 Jet fuel

The most common fuel for commercial aircraft is aviation turbine fuel, or simply jet fuel. The fuel is used in aircraft with turbine engines, which is the type of engine generally in use in big commercial aeroplanes for both passenger traffic and freight. There are also aircraft that are equipped with piston engines, and those use aviation gasoline. Aviation gasoline is a high-octane gasoline, with octane number of around 100. The piston engine cannot compete with the turbine engine in big aircraft since the piston engine is larger for a given effect (Huenecke 1997).

There are special specifications on aviation fuels since the environment in which it is used is changing a lot, from ground temperature, pressure and humidity up to marching height temperature, pressure and humidity. The vulnerability of being at such heights gives no allowance for failure due to fuel quality and the quality control of fuel is therefore thorough.

Jet fuel is almost exclusively extracted from the kerosene fraction of crude oil, which is those distillates between the gasoline fraction and the diesel fraction. Jet fuel mostly consists of straight run hydrocarbons in the range from eight to sixteen carbon atom compounds with a boiling range from about 150 to 300 °C (Speight 2007). That means that it is the kerosene originally in the crude oil, with no conversion processes included. The anti-knock value is of no interest (Air BP 2000).

A wide-cut jet fuel also exists which includes part of the gasoline fraction, compounds with five to fifteen carbon atoms. It was developed to increase the amount of available fuel but it is not used by civil aviation and its use as a military fuel has reduced (Air BP 2000). There are five basic grades of kerosene type of jet fuel that have commercial use today (Air BP 2000).

All the compounds of the fuel are not known, since there are no analysis equipment that can separate them all, but there are thought to be about a thousand different compounds. The overall performance of the fuel is what is important, not the exact content. The fuel is tested in a number of certified ways to be sure that it has the right properties. The tests are performed several times before the fuel finally is used in an aeroplane.

The kerosene fraction was from the beginning used as a lamp fuel and it was the most important fraction before petroleum's use in transportation. The quality of the kerosene fraction varies a lot with crude oil type. Mostly there is a need for further processing of the kerosene fraction, such as hydrotreating, for it to meet fuel specifications. Part of the fuel can come from heavier fractions of the crude oil, which has been processed in the hydrocracker unit. Addition of additives is the last step before the fuel is stored for delivery to customers.

Additives are chemicals that are added to give the fuel a special property. It can be an antioxidant to prevent oxidation or an icing inhibitor to stop ice from forming in the fuel. The additives are active in a very low concentration, the parts per million scale. (Chevron Global Aviation 2006)

The energy content of jet fuel must be high, combustion must be efficient under all flight conditions and it must be possible to relight the fuel when starting and landing. The combustion products and the fuel must not cause excessive engine deterioration, for example caused by un-combusted particles. The fuel must also have lubrication properties to sufficiently lubricate movable parts within the fuel system. It is important that the fuel can be handled easily and used to fuel aircraft safely at airports. The fuel has to have the right ignition qualities and that depends on the volatility and the viscosity of the fuel besides the design of the fuel spray nozzle in the combustion chamber and the fuel pressure. (Huenecke 1997)

One common commercial jet fuel is Jet A-1, in use for commercial aircraft outside the USA, Canada, China and East Europe (Air BP 2000).

In Table 5 are some specifications for jet fuel listed. There are also specifications on for example on corrosion, stability, conductivity, volatility and contaminants.

Table 5: Some specifications for the turbine fuel BP Jet A-1

Total acidity	0.003 (mg KOH/g)
Aromatics	19.5 % vol
Total sulphur	0.02 % mass
Mercaptan sulphur	0.0003 % mass
Flash point	42 °C
Density (15 °C)	804 kg/m^3
Freezing point	-50 °C
Specific energy	43.15 MJ/kg

(Air BP 2000)

5 Jet engines

A short look at the aeroplane engine can be well motivated to get a better picture of the jet fuels issue.

The four basic types of turbine engines for aircraft are turbojet, turbofan, turboprop and turboshaft engines. They work in slightly different ways but the main components are air intake, compressor, combustion chamber, turbine and exhaust nozzle. The engine takes in air through the air intake in the forward direction of the aeroplane. The air is then compressed by the compressor and after that it enters the combustion chamber. The air is mixed with fuel and that is ignited creating hot gases that increases pressure. The hot gas then expands through a turbine that drives the compressor and sometimes propellers. The remaining hot gas passes a nozzle on its way out, made to increase the speed of the gas. Pressure of the exhaust gas is converted to velocity of the gas, providing the aircraft with thrust, which moves the plane forward. The velocity of the exhaust gas is essential for the generation of thrust.

The most common type of engine for aircraft is the *turbofan engine* (Huenecke 1997). See Figure 8. What is special with the turbofan engine is that it has a low-pressure compressor, a fan, before the high-pressure compressor. The engine is constructed so that some of the air bypasses the second compressor and the combustion chamber and leaves the engine through its own exhaust nozzle creating cold thrust. The ratio in which the air is bypassed is called bypass-ratio. There are both high and low bypass-ratio turbofan engines. The high bypass-ratio turbofan type of engine has become popular because of its fuel efficiency and relatively low noise level due to lower velocity of the exhaust gas. Five times as much, or more, air is bypassed than is entering the engine proper (Huenecke 1997).

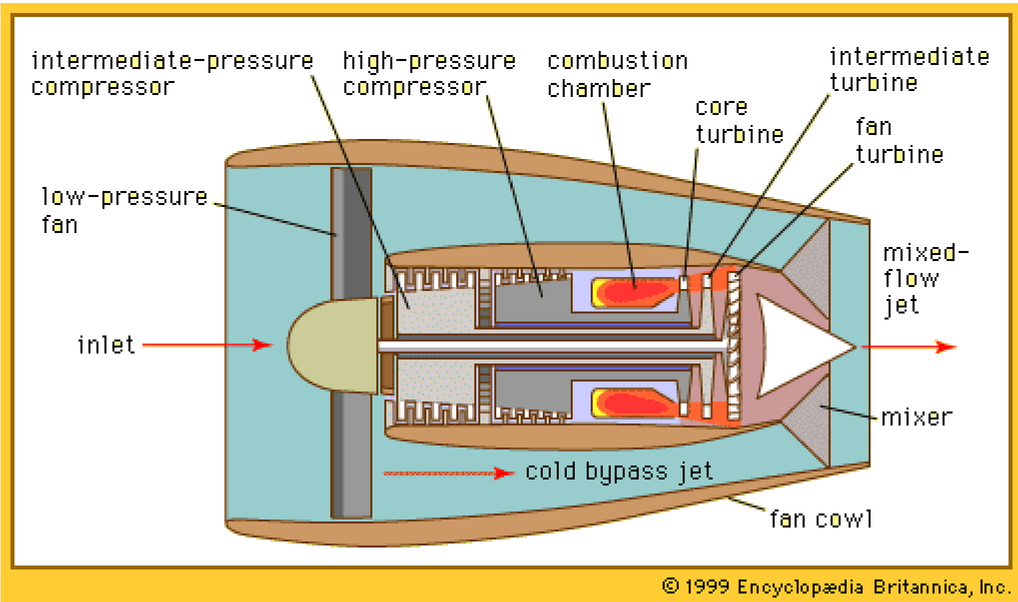

Figure 8: High-bypass turbofan engine. Source: Encyclopædia Britannica (1) 2008.

Turboprop engines are used on aircraft with propellers, more of the energy is then converted to mechanical energy in the turbine to drive the propellers. This kind of motor is the most energy efficient but it generates a lot of noise.

In a *turbojet engine* all air pass the combustion chamber generating thrust by high velocity of exhaust gases. The first engines of this type had small cross section area and relatively small air mass flow rate with, instead, a very high exhaust velocity of around 600 m/s, creating a lot of noise.

Turbo shaft engines are used in helicopters. All of the energy of the hot gas is transformed to mechanical energy in the turbine to move the rotor blades. Gas turbine turbo shaft engines can be used on ground to generate electricity by driving a generator.

5.1 Engine parts

It is important to design the *air intake* in a proper way to get a good airflow into the engine, the flow entering the compressor must be uniform and stable. The manufacturer of the aircraft is responsible for the design.

Most aircraft of today use axial *compressors* and their efficiency are 85 to 90 per cent (Huenecke 1997). The compressor is normally designed to meet one special flight condition, the design point, where the engine should deliver marked efficiency. The compressor also has to work well in off-design conditions, off-design performance, such as start and landing.

In the *combustion chamber* the fuel must be burnt with good efficiency to provide energy to the turbine. A perfect mixture of fuel and air increases the efficiency of the engine. To start the engine ignition by electrical spark is necessary, and then the combustion continues as a self-sustaining process. The goal is to combust 100 per cent of the fuel but some percentage of the fuel are generally not combusted or are not completely combusted. The efficiency of the combustion chamber is counted as the heat released divided by the theoretical heat available in the fuel. Today combustion chambers have efficiencies between 90 and 98 per cent. (Huenecke 1997)

The *turbine's* main task is to drive the compressor and propellers, if any. Turbines used in aircraft are of axial type and it works similar to the compressor, but reversed. The turbine has to survive extreme loads due to rotation and high temperatures since the inlet temperature is about 1300 °C. This requires special material and an advanced cooling system. The material is often a nickel-based alloy. The turbine should also give power to components like fuel and oil pumps and an electric generator. The turbine efficiency is between 78 and 92 per cent (Huenecke 1997).

The final part of the engine is the *exhaust nozzle*. The purpose of the exhaust nozzle is to transform the remaining energy in the exhaust gases to thrust that takes the aircraft forwards. The shape of the nozzle enables the transformation of the air mass pressure to velocity that creates thrust. The nozzle is basically an in area decreasing tube that creates convergence flow and in that way increases the speed of the exhaust gas.

5.2 Lubrication oil, starting system and pollution

Synthetic oils are used as lubrication in the jet engines. Synthetic oils are not manufactured from crude oil and the main reason for using synthetic oil is that it has almost constant viscosity down to temperatures of -40°C and a low viscosity can even be maintained below that temperature.

To start a jet engine a starting system is needed, a so-called *auxiliary power unit*. The starting system must accelerate the engine to ignition speed and then support the engine until a self-sustaining combustion can take place, this is termed engine idle. For a civil aircraft the starting system is needed for less than 30 seconds. The starter can be of different types, the most commonly used in civil jet aircraft is the air-turbine starter, others are electric starter and gas-turbine starter.

Pollution from aircraft is typically carbon monoxide, unburned hydrocarbons, unburned carbon and nitric oxides (Huenecke 1997). Also, of concern for climate change, is the carbon dioxide. The combustion is the main process to be changed to decrease exhaust gas pollution. For example do lower temperatures in the combustion chamber decrease the formation of nitric oxides. The nitric oxides are unwanted because they contribute to the acidification of the environment when reacting with water.

6 Alternative fuels

Research about alternative fuels is going on in the aviation industry, as in other motor industries. The high jet fuel price and the intention to lower emissions of greenhouse gases is the driver for this research. In February 2008 the airline Virgin Atlantic together with Boeing and the engine manufacturer GE Aviation did perform a test flight between London and Amsterdam. The aeroplane was a four engine Boeing 747-400 partly fuelled with biofuel. The biofuel was made from babassu and coconut oil and was blended in a 20 per cent mixture in one of four engines. The fuel was produced in a sustainable way in the sense that the nuts were taken from mature cultivations and did not compete with food production (Virgin Atlantic 2008). This was a first step towards flying on biofuels but there is still long way to go before biofuel can replace petroleum jet fuel.

The International Air Transport Association (IATA) aim is that 10 per cent of aviation fuels should come from alternative sources by 2017, alternative in the sense that their origin is not crude oil. This goal has evolved as a way to reduce carbon emissions and address global warming, but it will also serve to reduce aviation fuel consumption. The third generation biofuels, from plants not competing with food production nor other use (algae, jatropha, babassu for example), are the most interesting and the hope is that this kind of biofuels should be able to cover 100 per cent of jet fuel needs (IATA (2) 2008).

The introduction of alternative fuels can affect the entire aviation infrastructure and industry. The fuel most cost effective and easiest to implement is a fuel that is similar to today's jet fuel so that the same distribution channels and engines and aeroplanes can be used.

6.1 What alternative fuels are there?

The only alternative to jet fuel derived from crude oil in commercial use today is fuel from coal, so called *synthetic fuel*, it is produced with Fischer-Tropsch process by the South African company Sasol. The synthetic jet fuel is in a 50 per cent mix with petroleum jet fuel and approved for commercial traffic. Sasol is the only company today that uses this process to commercially produce fuel from coal. To increase the production of coal-to-liquids a lot of expensive refineries must be built. If the carbon dioxide is not captured the emission will be higher than from crude oil refining and use.

Liquid hydrogen is another fuel that is under consideration. A problem is that hydrogen must be produced. Production from, for example, electrolysis requires electricity and clean water and its environmental benefits depend on the energy source. Another problem is that the process is not energy efficient. To be able to use liquid hydrogen as fuel, changes must be done to the aircraft and fuel distribution system. For example the fuel tanks of the aircraft must be bigger and heavier and cannot be located to the wings, as they are currently. This adds weight to the aircraft that is somewhat compensated for by the lighter weight of the fuel on long trips. A change towards hydrogen-fuelled aircraft would take a very long time, and would only be beneficial if cheap hydrogen fuel is available (Daggett et al. 2006).

In the car industry *ethanol* has evolved as an alternative fuel. It can be manufactured from biomass. The ethanol however is not suitable for use in aircraft, the energy density is too low and it is not stable in the low temperatures that prevail at normal marching altitude. It would also require changes to the aircraft and make the fuel efficiency of the air transit lower.

Other *biofuels*, similar to biodiesel could be an alternative fuel for aviation. Probably the production of this fuel would require additional steps compared to biodiesel, to secure performance at higher altitudes (Daggett et al. 2006). Larger engine modifications could be avoided and the fuelling and storage systems would not need to be changed either. To produce biofuels in larger amounts is difficult, due to the limited area of arable land. First priority must be to cultivate food in a sufficient amount, but second and third generation biofuels that would not compete with food production are under development (IATA (2) 2008). The good thing about biofuels is that production can be done in a sustainable way without damaging the environment. Jet fuel from algae has been discussed, it counts as a third generation biofuel and appears promising. No competition with food production, with it being grown in saltwater compounds in, for example, a desert landscape. The algae produces extractable oil and they are fast growing under the right conditions but it is still unknown how big the real potential is.

The U.S. Air Force is pushing for alternative fuels, and the fuel that, according to them, has the best probability of succeeding is synthetic fuel from coal. Their goal is to be able to buy 9.5 million barrels of synthetic jet fuel in 2016, which would be about 25 per cent of their fuel needed for missions in continental USA. (The Wall Street Journal 2008).

Biofuels cannot replace all transport fuels, even if the aim was to only replace aviation fuel the challenge would be huge despite the fact that jet fuel is only a small part of total fuel consumption. The challenge or drawback for biofuels is land use, competition with food production, possibly low energy efficiency and the quality requirement of jet fuel. The conclusion is that a lot of hard work is needed to be able to replace even a small amount of jet fuel with biofuels in the near future. The only fuel that can replace some jet fuel today is synthetic fuel from coal, coal-to-liquids, but to scale up the production will take time.

7 Crude oil properties and origin

It is important to know something about the properties and origin of crude oil to understand the challenges for future aviation industries.

7.1 Properties of crude oil

Petroleum is a very complex collection of compounds. The liquid part of petroleum is called crude oil. The colour of crude oil goes from almost colourless to black and the viscosity, in room temperature, varies from easy flowing to almost solid. The composition of crude oil does not only vary between different fields, it is also likely to vary by depth and between different wells in the same field.

The true hydrocarbons in crude oil can be divided into three groups, which are paraffins, napthenes and aromatics. Most molecules in crude are not true hydrocarbons in the sense that there exist other atoms such as sulphur and nitrogen in their structure.

The *paraffin* hydrocarbons are those with saturated hydrocarbons in chains, branched or straight. *Napthenes* or alicyclic hydrocarbons are saturated, but the structure also consists of cyclic compounds. The *aromatics* include compounds with benzene structure. Benzene is a cyclic hydrocarbon with the formula C_6H_6 and it could be symbolized with a double bond between every other of the six carbon-carbon bonds. But in fact all the bonds are the same, sharing the extra valence electrons between them (Figure 9). The different compounds are mostly linked to each other in big molecules.

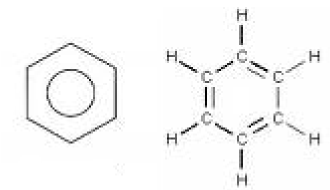

Figure 9: Two ways to represent the benzene molecule

The proportion between the compounds is often such that there are more paraffins in the lighter part of the crude, together with single-cycled napthenes. The dominating compounds in the heavy part of crude oil are napthenes with more than one cycle and aromatics (Speight 1999).

It is not possible to classify crude oil by the carbon content, as is done for coal, because there is little variation. The carbon content (from available data) varies between 83.0 and 87.0 per cent and the hydrogen content between 10.0 and 14.0 per cent. The content of other components are shown in Table 6, metals refer primarily to nickel and vanadium.

Table 6: Non-hydrocarbon content in crude oil

Nitrogen	0.1-2.0 %
Oxygen	0.05-1.5%
Sulphur	0.05-6.0%
Metals	<1000 ppm

(Speight 1999)

Of greater importance for the characteristics of the oil, other than the carbon content, is the shape and size of the carbon chains and where the non-hydrocarbon elements are situated. Unfortunately the shape and composition of the heavier parts of the crude is still unknown due to its complex nature and the lack of analysing capacity and methods.

The conclusion is that there is no easy way to describe existing crudes and in that way map the resources of petroleum. The amount of different products that it is possible to extract from the crude naturally depend upon its composition.

7.2 Classification of crude oil

It is not possible to work out a simple classification system for crude oil because of crude oils varying properties and complexity, even though lots of attempts have been made. Instead a *crude oil assay* is normally completed describing a lot of parameters enabling the best refining performance.

A crude oil assay can contain more than thirty different parameters for six to seven different distillation fractions for each crude oil. Examples of data in Statoil-Hydro's crude oil assays are (Statoil-Hydro 2008):

- API gravity
- Pour point
- Sulphur, nickel and nitrogen content
- Viscosity

Refineries need the crude oil assay to be able to adjust the refinery processing to work optimally for each crude purchased and to know what to buy. Still the assay, to some extent, is an approximate description of the crude delivered.

The first main classification system was based on the density of the crude, or actually the specific gravity (relative density) of the crude oil. The specific gravity is defined as the ratio of crude oil to water at 15.6 ° C. Most crude oil that is used today has specific gravity below 1, which means that it is less dense than water. The specific gravity is often changed into °API defined by the American Petroleum Institute as:

$$°API = \frac{141.5}{\text{Specific gravity}} - 131.5$$

Compared to water, crude oil with °API over 10 is less dense than water and crude oil with °API below 10 is denser than water. Light crude has gravities above 30 °API, medium crude has gravities between 20-30 °API and heavy crude oils has gravities less than 20 °API (Robelius 2007). This, pretty simple classification system, worked well as long as only one type of crude oil was in use. It was an indication of the gasoline content and, at first more interesting, the kerosene content. Now other types of crude oils are in use and the specific gravity is no longer significant as a measure of the quality of the crude oil. Even so, this classification technique is still in use for certain crude oils and products (Speight 1999).

7.3 Origin of crude oil

Crude oil is a natural product developed on earth during a long period of time a long time ago and it is finite natural resource, a so-called fossil fuel. The details of the origin of crude oil are not fully understood but it is clear that it is a none-renewable and a limited source of energy.

The origin of crude oil is plants and organisms that lived in shallow seas, deltas or lakes. These plants have later died and fallen to the bottom of the body of water with lack of oxygen and therefore have not decomposed in the usual manner. Over time the landscape changed and this assembly of un-decomposed material formed sediment and was buried in the ground, finally reaching a depth where the pressure and heat was sufficient to transform it into a material with high energy density and wide usability, crude oil. The interval of depth where crude oil can be formed is called the oil-window and is related to the earth's temperature. The oil-window is between 60 and 150 ° C, which correspond to a depth of about 2 to 6 kilometres, with a global average geothermal gradient of 2.6°C/ 100 m (Selley, 1998). If the temperature is too high natural gas is developed. The accumulation of material mainly happened during two periods of time, 100 and 150 million years ago. Fossil fuels can be seen as energy saved from biomass that grew million of years ago.

Very important factors for the formation of an oil reservoir with recoverable oil are:

- Reservoir rock
- Surrounding rock
- Source rock
- Migration conduit

Crude oil is not stored in an underground lake from where it can easily be pumped, but in a porous rock such as limestone, sand, sandstone or dolomite, that is the *reservoir rock*. A *surrounding* impermeable *rock* is necessary for maintaining the oil in place. The sealing rock can for instance be a shale or a clay. It is most likely that there exists a *source rock* where the crude oil was formed initially and from where the crude oil has migrated through for example fractures and porous rocks, the so called *migration conduit*, to the reservoir where it was trapped. (Speight 2007)

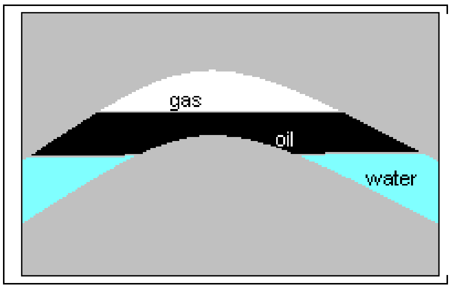

Figure 10: Anticlinal trap with gas at the top then oil and below that water, sealed by an impermeable rock.

The trap is a geological formation and it can be of different types, but with the conditions mentioned above met. One type is the anticlinal petroleum trap (Figure 10) where the reservoir rock is between layers of impermeable rocks and the tectonic movements have created level difference where the oil can be trapped due to density differences. There is often gas at the top, crude oil in the middle and water below.

The reservoirs are of different sizes, mostly small. A reservoir can be dived by other rocks, leading to crude oil accumulations that are not connected, making recovery more difficult and less economic.

All of the oil in the reservoirs cannot be recovered due to the characteristics of crude oil and the structure of the reservoirs. To be able to recover the oil it must migrate towards the well, but much of the oil is held in the ground by capillary forces. The recovery factor, the amount of oil possible to extract, is given in per cent and an average of the world is 40 per cent (Aleklett and Campbell, 2003). There are techniques to alter the amount of recoverable oil in a field, for example by water flooding (Speight 2007).

Important for a good recovery factor is the crude oil extraction rate, if it is forced too much there is risk of destroying the field. For example by what is called water-cut, water from the underlying layer breaks through to the draining place with the consequence of pumping water not oil. The possible oil recovery rate is an important factor for the supply of the world’s oil in the future.

8 Crude oil refining

It is important for a refinery to have good knowledge of the crude oil to be refined, making it possible to refine the crude in the most efficient and economic way considering the products desired (Speight 1999). Different crude oil qualities yield a different span of products and heavier oils require more refining, and there is also competition between the various products making it more complicated to calculate future supply of refined products.

It is also important for the refinery to be able to adapt to new regulations from society, changes in consumer demand and to the available crude oil. An example of a recent product is ultra-low sulphur diesel. All refineries are more or less different in their composition and have developed in to a complex collection of different process plants. How the refinery has developed is, together with the crude oil quality, essential to understanding how much aviation fuel can be produced.

The simplest refinery is called a *topping refinery* and consists only of a water treatment facility, plumbing, storing tanks and a distillation unit with a system for recovery of gases and light hydrocarbons. This kind of refinery mostly serves as a preparation plant for petrochemical manufacture or as a producer of industrial fuel in an oil producing country and is dependent upon the nearby market for its profitability.

If a hydrotreating unit and a reforming unit are added the refinery is called a *hydroskimming refinery*. This enables the refinery to produce most transportation fuels. Still a lot of possible high value products are lost as residues that have limited use and prize (Speight 2007).

A modern refinery is called a *conversion refinery*. It is a very complex and energy intensive production plant. Processes that take place on a conversion refinery include the ones mentioned above and for example vacuum distillation, catalytic cracking, hydrocracking, conversion plants and coking. It could also include units to produce for example lubricants or asphalt.

Jet fuel is extracted from the middle distillates fraction that also includes diesel fuel and kerosene for other use.

8.1 Refinery processes

The different processes in a refinery can be fitted into one of three categories: Separation, conversing and finishing (Speight 1999).

Separation includes the separation of different kinds of compounds from each other, as done in distillation towers. *Conversing* are processes where the original compounds of the crude oil are changed, for example thermal cracking. *Finishing* processes lead to final products and that include for example blending, purification and reforming.

8.1.1 Distillation

Distillation is a fundamental refinery process and it is a process used in many different production steps in a refinery. The various small distillation towers separate missing molecules and help purify different fractions.

Atmospheric distillation is the first refinery process for the incoming cleansed crude oil. The crude oil is distilled according to its volatility under atmospheric pressure in a distillation tower. The cleansed crude is heated in a furnace and partly evaporated and then moved to the fractional tower where the none-evaporated parts descend towards the bottom of the tower and the others rise towards the top. In the tower there are a number of plates or trays that help separation of the fractions, that can be collected as side-streams and withdrawn. These fractions still contain higher boiling compounds and are past into a stripper to remove the more volatile components. It is important to not have too high a temperature in the column to avoid cracking that can form coke in the tower (Speight 2007).

The fractional distillation gives a classical picture of a refinery but it is only one process of many to come, to obtain finished products. The division of the distillation fractions into different ranges can look a bit different. This is one version:

Fuel gas:	Hydrocarbons in gaseous form, consisting of short carbon chains up to four carbon atoms (butane). This gas is used within the refinery or sold as LPG (liquefied petroleum gas).
Light naphtha:	Have a boiling range from –1-150 °C. Obtained through condensation of the fraction containing the fuel gas, for example added to gasoline.
Gasoline:	Boiling range -1-180 °C. Transport fuel, mostly for cars, need further processing.
Kerosene:	Boiling range 150-300 °C For example feedstock for the manufacturing of jet fuel.
Light gas oil:	Boiling range 260-315 °C. Feedstock for the production of diesel fuels.
Heavy gas oil:	Boiling range 315-424 °C. Needs processing to turn into more beneficial fractions or used as heating fuels or in tankers (bunker fuel).
Residue:	Boiling point over 425 °C. Consists of the heavier part of the crude oil even though lighter parts still exist among the others. It is further treated in the refinery.

All of the fractions obtained in the first distillation need more or less processing to meet today's product requirements.

For the atmospheric distillation residue the next step could be vacuum distillation. The procedure is similar to the atmospheric distillation but the vacuum is held under the distillation.

8.1.2 Thermal processes

Thermal processes are conversion processes where temperature is important for the outcome. Cracking is the term for decomposition of big molecules into smaller ones.

Example of processes: thermal cracking, visbreaking and coking.

Thermal cracking was one of the first processes invented to increase the yield of gasoline from crude oil but can favourably be replaced with catalytic cracking. Visbreaking is a gentle form of thermal cracking and coking is complete thermal conversion of the feedstock into gases, naphtha, fuel oil, gas oil and petroleum coke.

8.1.3 Catalytic and hydrogen processes

Cracking of oil can work much better with the help of a catalyst, meaning that more, higher quality products can be obtained. Several different catalysts are in use.

Hydrogen is also very important for a modern refinery, it takes part in many processes improving the yield and the fuel quality, removing non-hydrocarbon elements, mostly together with a suitable catalyst. The need for hydrogen increases with heavier feedstock, since it needs to be reformed to a higher grade. The catalytic reforming, where straight gasoline compounds are reformed to branched isomers, has hydrogen as a rest product. The hydrogen is taken care of and used in hydrogen requiring processes, but it is still necessary with an additional source of hydrogen. The most common way to produce that hydrogen is to use *steam methane reforming* or *oxidation processes* (Speight 2007). Natural gas is often the raw material for the hydrogen production.

Hydrogen is used in excess in most of the processes and therefore a relatively big amount of hydrogen can be recycled and used again (Speight 2007). The hydrogen system can be a limiting factor for the refinery if it is not adequately constructed and of sufficient size.

The hydrogen and catalytic processes include both conversing and finishing.

Examples of processes are: catalytic cracking, hydrotreating, hydrocracking, reformation, isomerization, alkylation and polymerization.

8.2 Heavy feedstock

Heavy crude oil, tar sand and residue from distillation have a character of low API gravity (high density), high viscosity, high temperature of initial boiling point, high carbon residue, high content of nitrogen, sulphur and metals. The average molecule weight is greater and the hydrogen content lesser for these heavy parts (Speight 2007). Heavy crudes need more processing to yield high value products.

Heavy crude oil is an increasing part of the world market due to the diminishing amount of lighter qualities.

8.3 Refinery products

A modern refinery produces a great variety of products. But it is the demand for vehicle fuels that has been the driving force for their development and most refineries try to boost the production of high value fuels, such as gasoline, diesel and to some extent jet fuel. Other products are, for example, solvents, asphalt and lubricants and feedstock for other industries such as plastic, cloth, and insecticide industry. Actually there are thousands of different products originating from crude oil.

There exist product specifications and standards for the different refinery products. That is certainly important for both the refinery and the consumer of, for example, gasoline. The refinery need to know how to process the fuel, the manufacturers of cars need to know what fuel they should optimize the car for and for the user it is essential to know that they have access to the right kind fuel for their car. The ones setting and holding standards are for example the American Society for Testing and Materials (ASTM), International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC). For aviation fuels the British Ministry of Defence and International Air Transport Association Guidance Material (IATA) are also important (Air BP 2000).

8.4 Energy consumption at the refinery

A large amount of energy is needed for the crude oil refining processes, a refinery can be counted as a high-energy process industry. In a refinery the share of crude oil used for internal energy generation is 4-8% depending on its complexity level (Ocic 2005). More complexity means more process units on the site. Refineries also use electricity, for example to drive pumps and control-equipment. A lot of water is also used. Some of this water can be purified and recycled, some becomes waste water.

8.5 Refinery emissions and waste

A refinery generates emissions and waste products. Typical emissions are volatile organic compounds, carbon monoxide, sulphur oxides, nitrogen oxides, ammonia, hydrogen sulphide, particles, metals, spent acids and several toxic organic compounds. The emissions or wastes can be in gas, liquid or solid form (Speight 2007).

The gaseous emissions are the hardest to capture, leakage from pipes, pumps, valves and such are often the largest source.

The liquid wastes are in form of waste water from the process, storm water and cooling water and are mostly treated on the refinery site. The water treatment generates solid waste and air emissions.

Waste in the solid form comes from waste water treatment, crude oil handling and many of the refinery processes. Solid waste can be spent catalysts, sludge from alkylation and isomerization and coke dust. These wastes can be both harmful and harmless and are treated and disposed of in different ways. Metals are often recovered and recycled. (Speight 2007)

Jet fuel is part of refinery production and therefore a contributor to waste and emissions.

8.6 Aviation fuel part of refinery production

Aviation was 6.3 per cent of refinery production in 2005 (Figure 2), but it is not a fixed number. In 1973 the aviation fuel part of refinery production was 4.2 per cent and since 2001 the number has been between 6.0 and 6.3 per cent. The aviation fuel volume has changed a lot, from 114 Mt in 1973 to 238 Mt in 2005 (IEA Key World Energy Outlook).

Aviation fuel is not only jet fuel from the kerosene fraction but also aviation gasoline. Aviation gasoline is a small product compared to jet fuel, but it is still included in the 6.3 per cent.

The kerosene fraction is an average of 8-10 per cent of the crude oil, but all kerosene does not become jet fuel. Kerosene is, for example, used to decrease the viscosity of the heavy fractions and can also be added to the diesel fraction (see chapter 9). Kerosene is also used as lamp oil in some parts of the world.

Simple refinery process changes could increase the jet fuel production and if the hydrocrackers were optimized to produce jet fuel the share could probably increase much more (Wernersson 2008). To be able to produce even more jet fuel new hydrocrackers could be developed, but that would take time.

Production changes in the refinery only change the yield of different products. If jet fuel production were to increase obviously the production of other products would decrease, such as gasoline and diesel. The refinery produces what is most profitable and adaptations to produce more jet fuel will not happen if the demands for other products do not decrease, or unless airlines are prepared to pay more than other customers.

9 Case study of an refinery

The type of crude oil used in a refinery and the products manufactured are to some extent possible to vary, two Swedish refineries are taken as an example of the effect this can have on jet fuel production.

The refinery Preemraff Gothenburg is situated on the west coast of Sweden outside Gothenburg, owned by Preem Petroleum AB. The crude oil arrives by pipeline from a nearby harbour. Finished products are transported by pipeline to the oil terminal at another nearby harbour and mostly leave by ship.

All the processes in the refinery are fuelled by fuel gas, which is the lightest fraction from the fractional distillation. The exceptions are two boilers that can be fuelled with fuel oil and the crude oil furnace for heating the crude oil. The energy efficiency of the refinery has increased due to the installation of a system that can compress and save surplus fuel gas.

The atmospheric distillation process divides the crude oil into five different fractions, the second fraction is about 33 per cent of the crude oil and contains the raw material for jet fuel production. This fraction is further processed in the Distillate Hydrotreater (DHT). The DHT process improves the properties of the kerosene fraction, sulphur is reduced and some of the aromatics are converted to napthenes, which gives cleaner combustion. The yield from the DHT is jet fuel and feedstock to reformer and isomerization units for gasoline production. The DHT also yields propane and butane that will be converted into liquefied petroleum gas (LPG) and lighter hydrocarbons that will be fed to the fuel gas system within the refinery. About 14-15 per cent of the feed to the DHT becomes kerosene, producing a kerosene fraction of around 4 to 5 per cent of the crude oil, but this number is dependent on the crude oil used.

In 2007 the crude oil input was 4.56 million tonnes, which is about 33 million barrels. The jet fuel production was about 12 000 cubic meters, which corresponds to 75 500 barrels or to 9670 tonnes (BP, Standard Conversion Factors). Jet fuel production was about 0.2 per cent of the crude input, which is a lot less than the original kerosene fraction of 4 to 5 per cent. The kerosene that is not sold as jet fuel is mostly contributing to diesel production.

The size of jet fuel production at the refinery is dependent on various parameters.

- The market situation at the moment.
- The grade/quality of the crude oil processed
- The logistic situation at the refinery

The refinery is flexible in their production when it comes to producing diesel and jet fuel. The different fuels are to a greater extent competing for the same hydrocarbons. The decision of what to produce is based on what is more beneficial to produce, jet fuel or diesel, from an economic point of view. There are also some additives to jet fuel that must be taken into account when deciding which product to produce, since additives add costs to production. The logistic situation refers to the storage situation on the refinery since jet fuel must be separated from other products in a special way.

If the refinery wants to increase their jet fuel production the diesel production would necessarily decrease. This also implies that jet fuel production could be increased without large investments or time delays and during the year the proportion between diesel and jet fuel production changes.

The crude oil purchased for Preem refinery in Gothenburg is mostly sweet North Sea crude. Usually the crude oil is defined by a crude oil assay, valid until the supplier indicates change. The quality of the crude oil input to the refinery can still shift a bit from one load to another of the same crude oil. Between different crude oils there are quite large differences in product yield, hence different crude oils give different yields of jet fuel.

The other fractions from the crude oil distillation are about 20 per cent light gas oil, 20 per cent heavy gas oil and 27 per cent residue. The light gas oil is fed to the Synsat unit where sulphur and nitrogen are reduced and aromatics saturated to manufacture low-sulphur diesel. The heavy gas oil goes to mild hydrocracking to increase the yield of fuels. The refinery has no vacuum distillation equipment to upgrade the residue so it is sold. The refinery is completed with two units to extract sulphur from the sulphur rich gas that is a rest from the desulphurization units. Liquid pure sulphur can be sold as by-product.

The efficiency of the refinery is improved through delivering excess heat to the district heating system of the nearby city of Gothenburg, each year of about 450 GWh.

(Åhman 2008 and Preem 2008)

Preem petroleum AB has another refinery, Preemraff Lyseklil, more adapted to heavy crude oil. Swedish Environmental class-1, ultra-low sulphur, diesel is one of their specialities. They have no jet fuel production, the kerosene fraction is blended into the diesel instead to give the right viscosity properties. Having fewer products is a way to increase the efficiency of the refinery. (Preem 2008)

10 Peak oil

There are different opinions about future crude oil production. Some are much more optimistic when it comes to the amount that can be produced than others. In this report two more restrictive views of possible production will be taken into account. The availability of jet fuel is dependent on crude oil production.

10.1 Production and consumption of crude oil

The crude oil deposits are not evenly distributed among the states of the world, neither is its consumption. From this simple picture (Figure 11) it can be seen that demand and production do not match very well at all. There is huge demand in the United States, Europe and Asia Pacific, fed by Russia, the Middle East, Africa and to some extent, South America. In 2007 crude oil production decreased by 0.2 per cent to 81.5 Mbbl/day compared to 2006 (BP (2) 2008).

Consumption data from BP included consumption at sea, land and air. It also includes internal refinery consumption and ethanol and biodiesel. The production data from BP includes crude oil, shale oil, oil sand and natural gas liquids. Biofuels are not taken into account in production. The numbers are in million tonne per year.

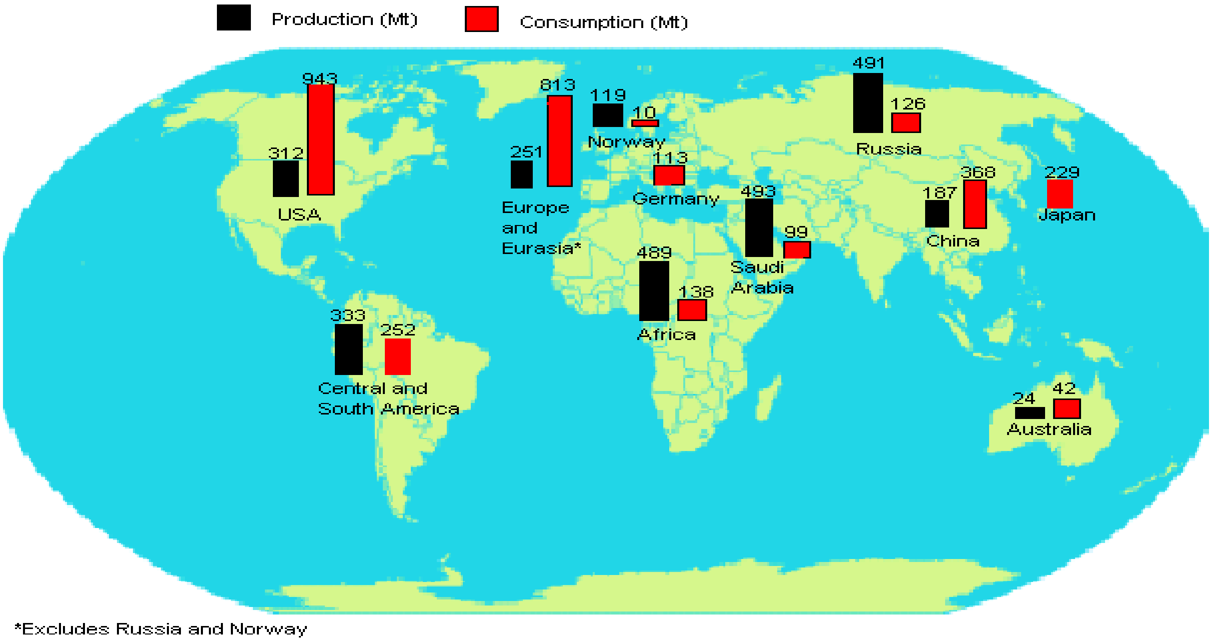

Figure 11: Map over some of the big consumers and producers (the bars are not in scale) Source: Data from BP Statistical Review of World Energy 2008.

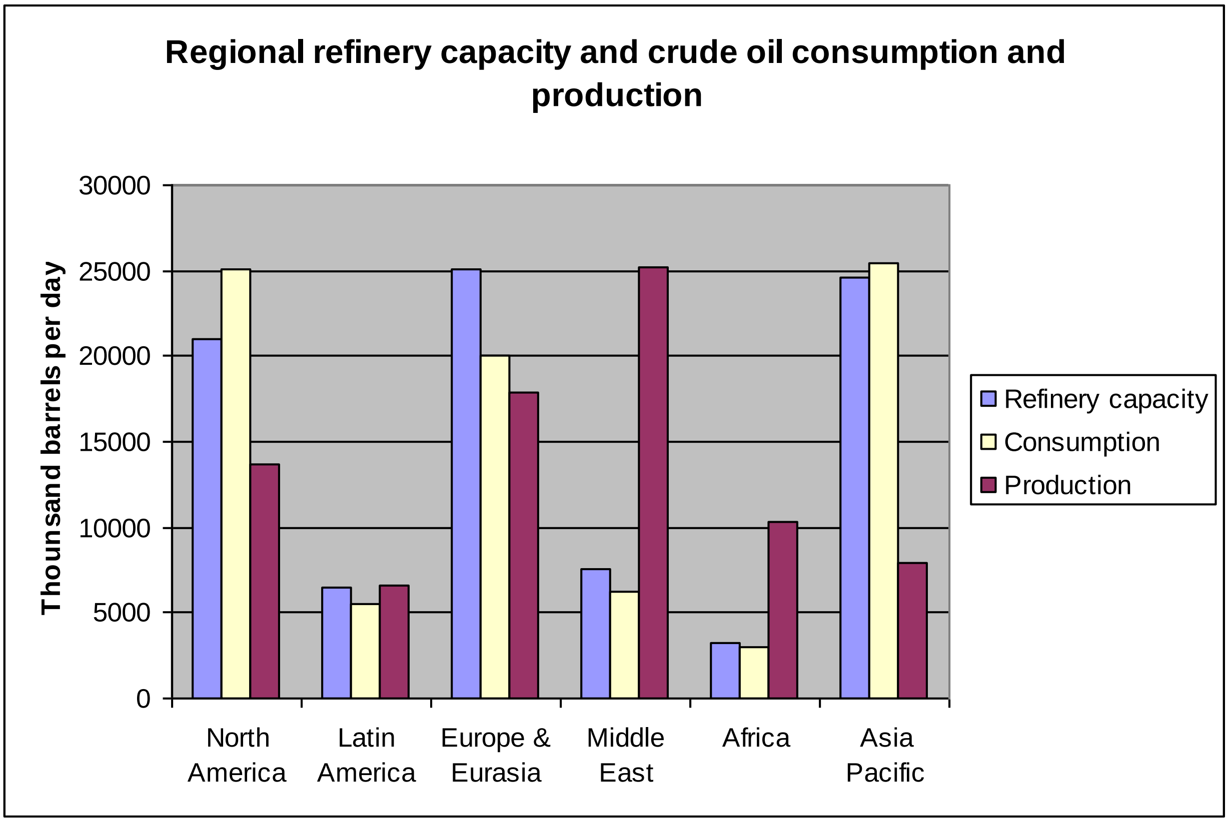

Figure 12: Crude oil consumption and production by region 2007. The refinery capacity data is for atmospheric distillation capacity. Source: Data from BP Statistical Review of World Energy, 2008.

Consumption and refinery capacity are much closer to each other than production and refinery capacity. Most refineries are situated near to market, as can be seen in Figure 12.

10.2 Peak in crude oil production

Oil, being a finite resource has been known for a long time, but the date when oil production would start to decrease has always been moved forwards in time due to the discovery of new fields and improving technology and thereby increasing the amount of recoverable oil.

The term Peak Oil is defined as: *"The term Peak Oil refers to the maximum rate of the production of oil in any area under consideration, recognising that it is a finite natural resource, subject to depletion"* (Campbell 2001).

What is difficult and subject to discussion and research is not that oil production will eventually peak, but the time that it will happen. This lack of agreement can have its base in the economic and the physical viewpoint of the problem respectively. One reason for this problem is the oil reserve reporting practice that has evolved, only the reserve that is recoverable for the moment is reported, with the effect that it seems like oil companies have been able to increase their reserves every year, without finding new fields in reality. (Aleklett and Campbell, 2003).

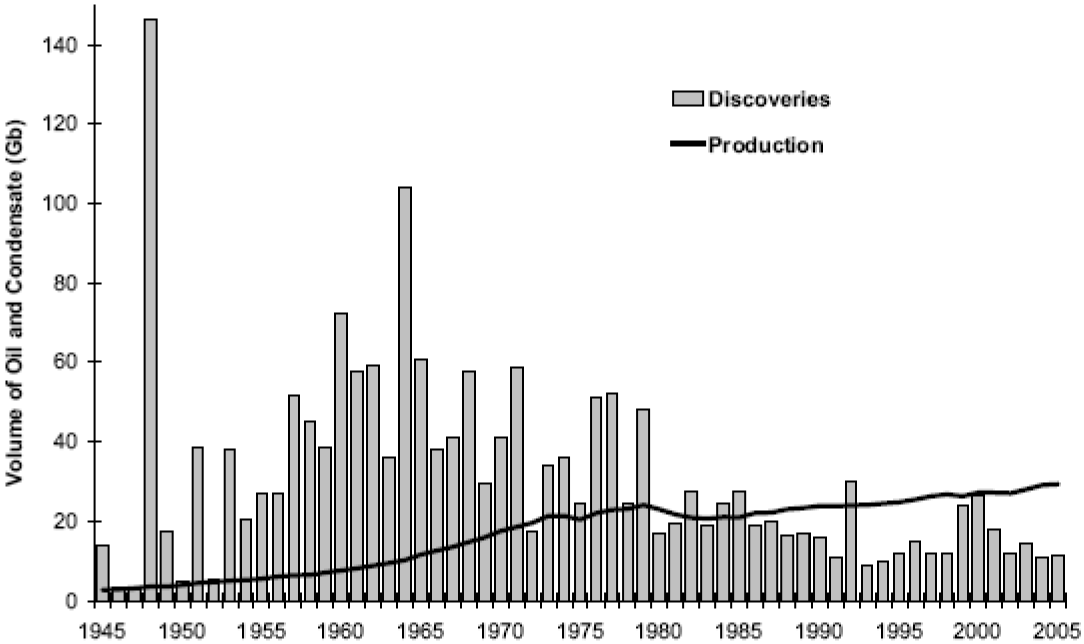

Figure 13: Discovered new oil fields and production in Giga barrels per year. Source: Robelius, 2007.

The discovery trend of crude oil can be seen in Figure 13. Most of the crude oil was discovered in the sixties, and with some exceptions less oil has been discovered since.

The size of the reserve is not known in absolute terms until the production at the field ceases and what makes it even more complicated to predict future crude oil production are that the reporting of the reserve numbers from some countries lack transparency (Aleklett and Campbell, 2003). It has been claimed that some countries in the Organization of Petroleum Exporting Countries (OPEC) possibly have overstated their reserves, revising their numbers up in the eighties, to protect their production quota (Robelius, 2007). The OPEC-countries co-operate and decide on petroleum production, usually done by deciding quotas with respect to a county's total crude oil reserve. It can also be seen that there is little change in some OPEC-reserve data, despite the continuous extraction of oil (Aleklett and Campbell, 2003).

10.2.2 Peak Oil and Giant Oil Fields

At Uppsala University a modelling of future oil production was completed in 2007 (Robelius 2007). The model is based on production from giant oil fields, fields with ultimate recoverable reserves of at least 500 million barrels. The ability of a giant field to produce large volumes during a long time means they dominate world supply. A lot of small fields cannot compensate for a decrease in production in the giants because of their much lower production rate. The conclusion is that production in the giant fields determines the world peak in oil production (Robelius 2007). The model has been constructed to make an estimation of the time when the peak will occur and four different scenarios of future production were developed.

The peak in crude oil production has been calculated to occur between 2008 and 2013 or as late as 2018 if adjusted to the IEA prediction of future oil demand (Figure 14).

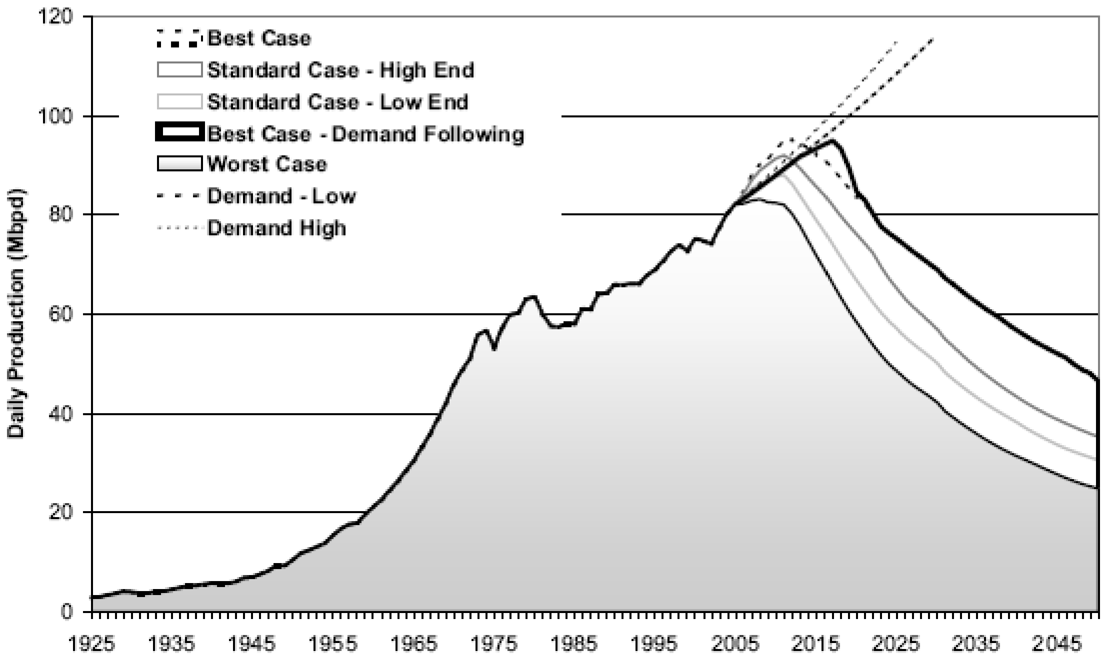

Figure 14: Demand adjusted scenario for Peak oil, including four different scenarios. Daily production in million barrels per day. Source: Robelius, 2007.

The prognosis takes into account new projects that could contribute to production and also deep-water production, heavy oil from the Orinoco belt in Venezuela, tar sand in Canada and natural gas liquids (NGL) (Robelius 2007). That is hydrocarbons from two to eight carbon atoms that originate from natural gas production. NGL can partly be a component in gasoline, so called natural gasoline. Still the overall production is forecast to decrease with production in the giant fields.

The latest giants were probably found in 2007, in the sea outside Brazil (Upstream 2007). A giant oil field is easier to find than a smaller field, making it improbable that a big amount of giant fields will be found in the future.

10.2.3 Peak Oil and Energy Watch Group

The Energy Watch Group (EWG) has done another outlook on future crude oil production. The EWG consists of independent experts and scientists and the purpose of EWG's work is to investigate concepts for a sustainable global energy supply, and the group produced their report on future crude oil supply in October 2007.

The outlook is, above all, based on an industry database on past production data and to some extent on reserve data. This approach was chosen since past production data is the most reliable data. Sometimes though the group found it necessary to do well based data estimations.

The conclusion from the work done by the EWG is that oil production peaked in 2006 and that it now will go down by several per cent each year, and that it will be hard to fill the gap with other energy sources (EWG 2007).

10.3 Petroleum in Society

Why are crude oil products so important? Because products made from crude oil or most of all, energy from crude oil has been the driver of the development of the modern society and it has built up the wealth that can be seen in the west.

There is a correlation between the oil usage per capita, living standards, and the wealth of the people (Jakobsson 2007). Huge amounts of very cheap energy have been available creating economic growth. Fossil fuels, and above all those derived from crude oil, are extremely important for modern society and not only as fuels. Other products such as plastics, asphalt and medicine are made from oil. The society of today, above all, the developed world is simply very dependent on those products originating from crude oil for everyday life. One of these products is jet fuel that, with few exceptions, is the fuel used by the world's fleet of aeroplanes.

11 Future scenarios of aviation fuel supply and demand

In this chapter the calculations that are made of future aviation fuel demand and supply are presented.

11.1 Future aviation fuel consumption scenarios

Four scenarios have been constructed for future aviation fuel demand. The scenarios are based on the industry forecasts reviewed in Chapter 2 and 3, both when it comes to air traffic growth and goals for fuel efficiency increase.

- A: Air traffic will keep growing according to industry forecasts and the average fuel consumption of the world aircraft fleet will stay as it is today. Fuel consumption will increase at the same rate as air traffic.
- B: Air traffic will keep growing according to industry forecasts but average fuel consumption will decline by 50 per cent compared to 2005 by the year 2020. A decrease by 1 per cent a year from 2020 to the year 2026 is assumed.
- C: Air traffic will keep growing according to industry forecasts, the average fuel consumption will decrease by 25 per cent by the year 2020 with respect to 2005. A decrease by 1 per cent a year from 2020 to the year 2026 is assumed.
- D: Air traffic will keep growing and average fuel consumption will follow a curve (Figure 18) extrapolated from the average fuel consumption for the years 1987 to 2007.

11.2 Base for the calculations of future jet fuel demand

The forecast number for RPK growth is used as an indicator of growth of jet fuel consumption since it is better coupled to fuel use than the number of passengers travelling. Traffic volumes for freight is given in tonne-kilometres but those numbers have been converted to passenger-kilometres since no number was found on fuel consumption per tonne-kilometre.

The calculations of future aviation fuel demand have been based on aviation fuel production in year 2005 or normalized to the production that year, since that was the latest available aviation fuel production number from the IEA. Aviation fuel production was 238 million tonnes, 6.3 per cent of refinery products the year 2005 (Figure 2).

In Table 7 a summary of the scenarios A, B, C and D can be seen.

Table 7: Summary of future aviation fuel Scenario A, B, C, and D

Scenario	A	B	C	D
RPK growth/year	5 %	5 %	5 %	5 %
Goods traffic growth/year	5 %	5 %	5 %	6.1 %
Starting value aviation fuel consumption	238 Mt	238 Mt	238 Mt	238 Mt
Start year	2005	2005	2005	2005
End year	2026	2026	2026	2026
Fuel efficiency improvement/year	0	4.5 % to 2020 then 1 %	1.9 % to 2020 then 1 %	2 %
Increase fuel consumption/year	5 %	0.3 % to 2020 then 4 %	3 % to 2020 then 4 %	3 %

11.2.1 Future aviation fuel consumption of Scenario A, B and C

In Scenario A fuel consumption from 2005 has been increased by 5 per cent a year, which corresponds to the RPK growth from the Boeing forecast (Table 1). The Airbus forecast predicts 4.9 per cent growth (Table 3) but only the 5 per cent value was used since the difference is minor.

To separate aviation traffic growth from aviation fuel consumption growth calculations were made with fuel consumption reductions of 25 and 50 per cent to 2020, scenarios B and C respectively. The fuel efficiency increase was calculated as a yearly efficiency gain. The continued decrease of 1 per cent a year to 2026 was chosen by the author because no aviation industry goal is mentioned after 2020. No difference between passenger and freight traffic was made in Scenario A, B and C.

The resulting forecast for aviation fuel consumption can be seen in Figure 15.

11.2.2 Future aviation fuel consumption of Scenario D

Aviation fuel consumption outlook for Scenario D was calculated based on earlier improvements to the global air fleet average fuel consumption. Improvements gained during 1987 to 2007 were extrapolated to year 2026. A hyperbolic extrapolation was chosen instead of a linear one, since it is not possible for the fuel consumption to go to zero (Figure 18).

The values for average fuel consumption have been multiplied with aviation traffic data and, by Boeing, predicted growth rate of passenger- and tonne-kilometres to calculate future aviation fuel consumption. Traffic numbers used were only for scheduled revenue traffic, which give lower fuel consumption than in reality. The fuel consumption was therefore normalized to the aviation fuel production of 2005 of 238 million tonnes. The passenger traffic was assumed to grow by 5 per cent and goods traffic by 6.1 per cent a year (Table 1).

The resulting forecast for aviation fuel consumption of Scenario D can be seen in Figure 19.

11.3 Future aviation fuel production scenarios

Those are the crude oil production scenarios that the calculations of future aviation fuel production are based on, 6.3 per cent of crude oil is assumed to become aviation fuel.

1: Oil production will follow the forecast made by the Energy Watch Group in *Crude oil – the supply outlook*.
2: Oil production will follow the best-case scenario of the forecast made by Robelius, in the doctoral thesis *Giant oil fields*.
3: Oil production will follow the worst-case scenario of the forecast made by Robelius, in the doctoral thesis *Giant oil fields*.

These scenarios will be compared to the jet fuel consumption scenarios A, B, C and D.

11.4 Base for the calculations of future aviation fuel production

The scenarios 1, 2 and 3 for future crude oil production are used to calculate possible aviation fuel production in the future. Aviation fuel is put at 6.3 per cent of total forecast crude oil production in case 1, 2 and 3 respectively, and then production is normalized to the value of aviation fuel production of 2005, that is the real value for aviation fuel production in that year.

The industry forecasts for aviation traffic go to 2026 and that is also the end date for this outlook.

For the calculations in this thesis the aviation fuel production is fixed to be 6.3 per cent of crude oil production. Varying this number will give different outcomes for the available amount of jet fuel in the future. A reason for keeping it fixed is that competition from other products is strong (see Chapter 8.6).

12 Results

The result is a forecast for future aviation fuel demand and supply to the year 2026 based on the scenarios described in Chapter 10.

12.1 Peak oil and aviation fuel demand based on fuel production year 2005

Figure 15 shows future aviation fuel consumption of Scenario A, B and C.

Fuel efficiency improvements have a large impact on the result for the forecast for aviation fuel demand in the year 2026. If nothing is done 662 million tonnes is forecast to be required, 18 per cent of the world's refined products in the year 2005, Scenario B and C would give a demand of 468 or 315 million tonnes respectively.

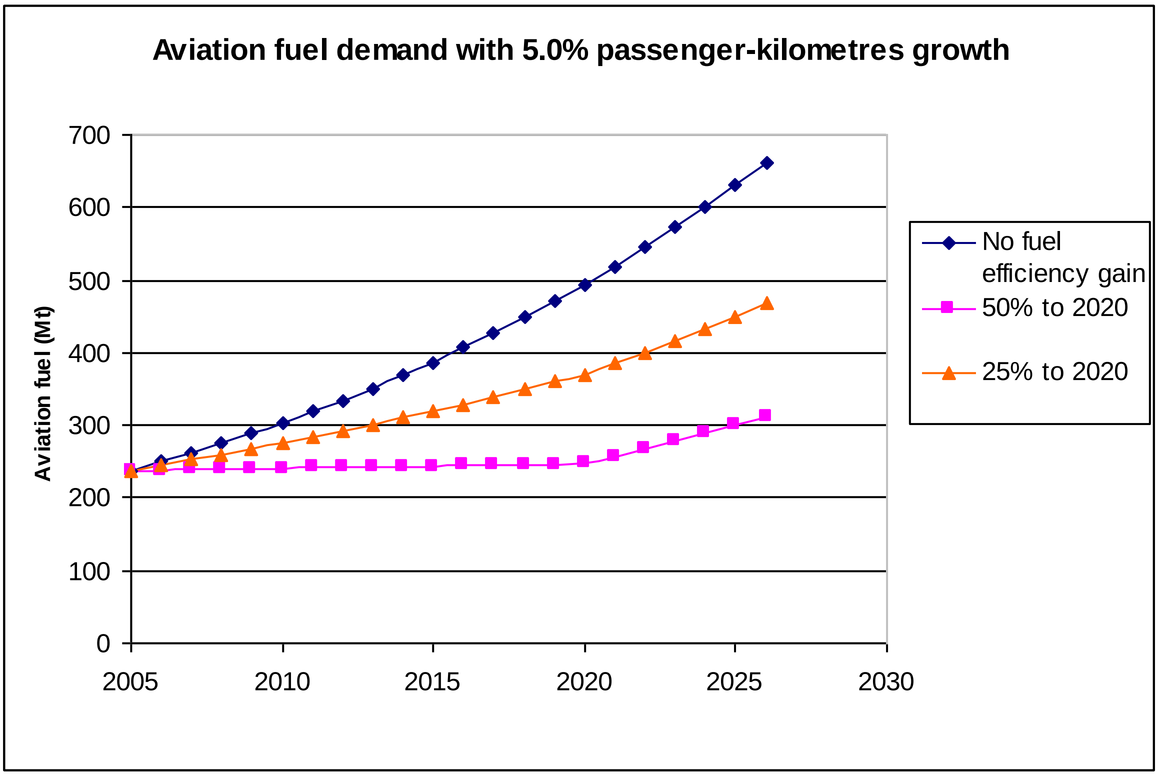

Figure 15: The growth in demand for aviation fuels with a forecasted 5 per cent growth of passenger-kilometres flown. Starting value is the 2005 consumption of aviation fuel. Scenario A, B and C. Source: IEA 2007 and Boeing 2007.

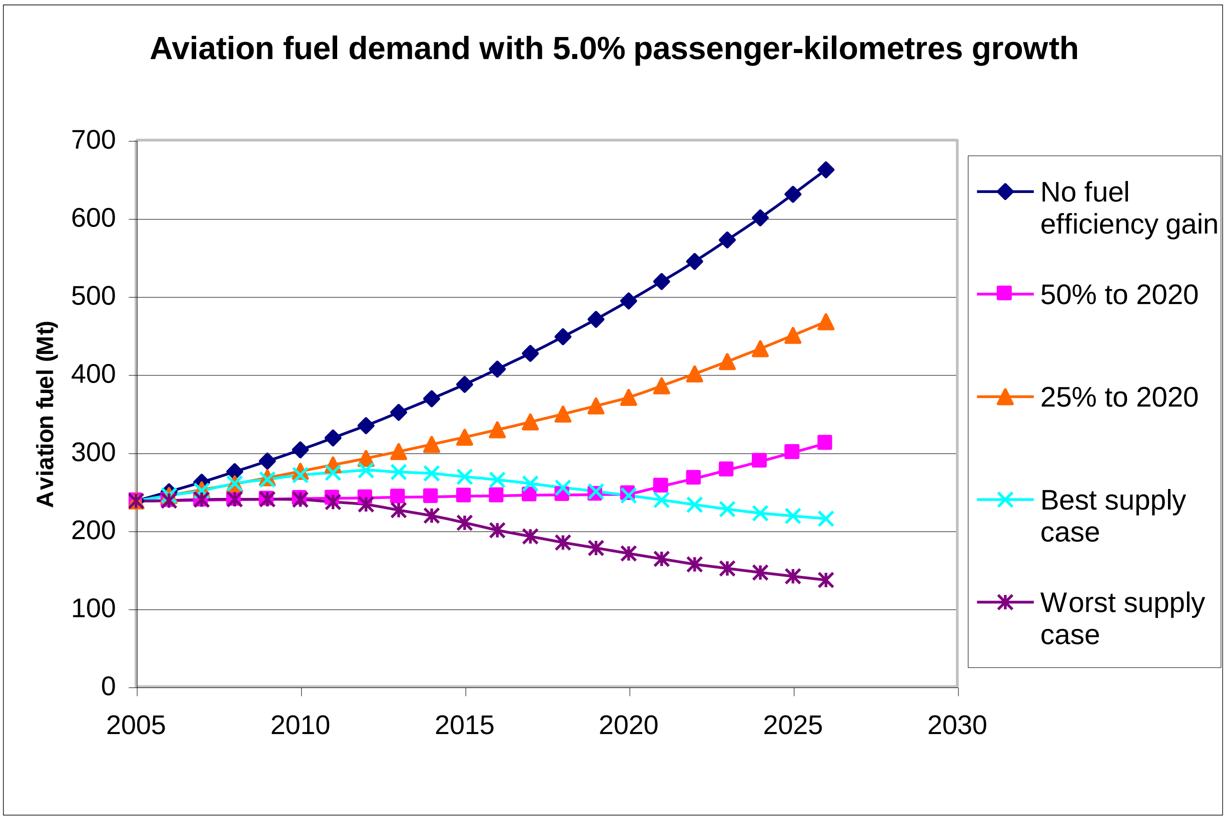

Figure 16: Future aviation fuel demand compared to peak oil Scenario 2 and 3. Source: Data from Robelius, 2007, IEA 2007 and Boeing 2007.

In Figure 16 the aviation fuel demand for Scenario A, B and C are compared to Peak oil Scenario 2 and 3 described in Chapter 11.1 and 11.3 respectively. It can be seen that there will be a lack of aviation fuel in all cases by 2026, but that Scenario C and Scenario 1 shows a surplus of aviation fuel until 2020.

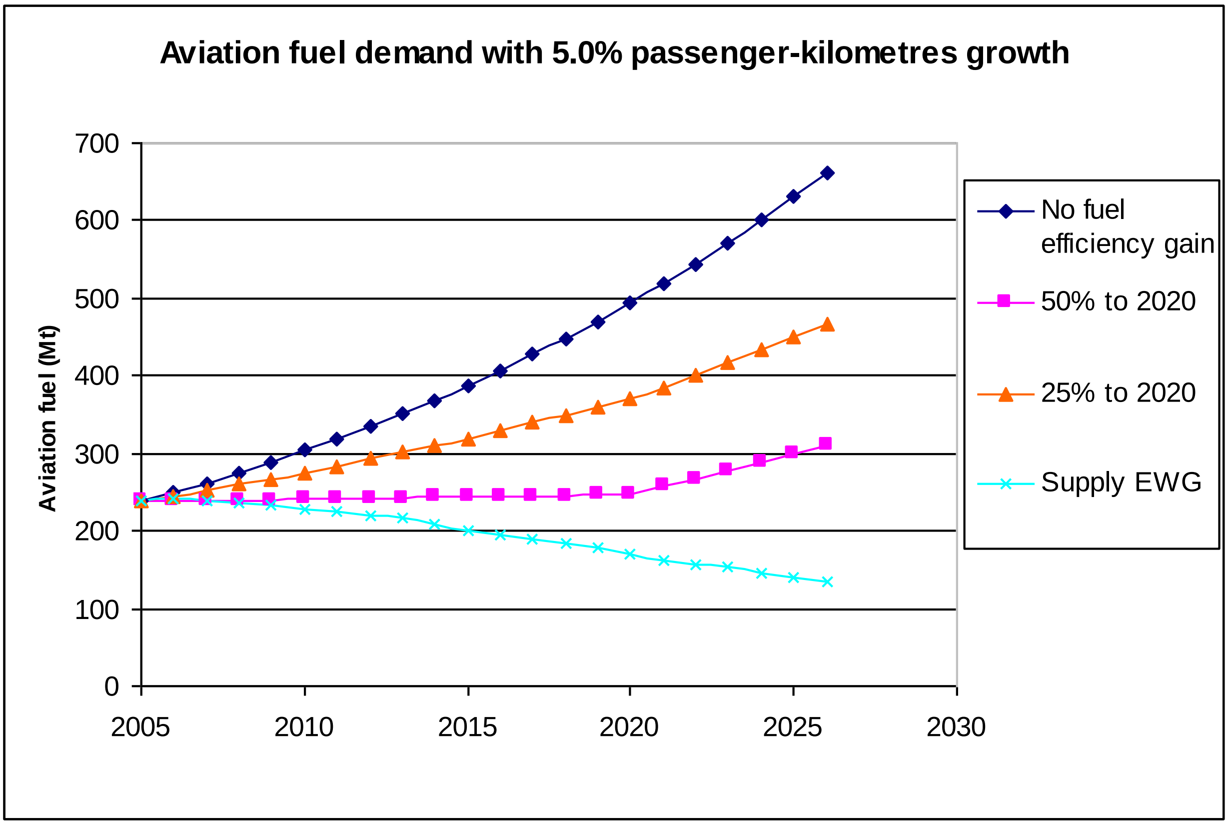

Figure 17: The demand for aviation fuel in contrast to the fuel availability according to Scenario 1. Source: Data from EWG 2007, IEA 2007 and Boeing 2007.

In Figure 17 the aviation fuel demand forecast of Figure 15 is compared to the production forecast of Scenario 1. The forecast for aviation fuel production of Scenario 1 is similar to the result of Scenario 3, with the difference that the decline starts earlier but has a decline rate per year that is less.

12.2 Comments on the results

Normalising aviation fuel production and consumption to 2005 was performed because, at the time, that was the most recent numbers for aviation fuel production found. The effect of this normalization on the result is that it, in some cases, it appears as if a lack of aviation fuel has already occurred. In reality that has not happened and therefore production must have been larger, or consumption less, than in these figures.

12.3 Peak oil and aviation fuel demand based on world fleet average fuel consumption

Figure 18 shows the development of the average fuel consumption of the world aviation fleet and the extrapolated values. The extrapolation gives an average consumption 3.3 litres/100 RPK in 2026. Airbus forecasts the fuel consumption to 3 litres/100 RPK (Airbus 2007). A linear extrapolation would have given 2.3 litres/100 RPK.

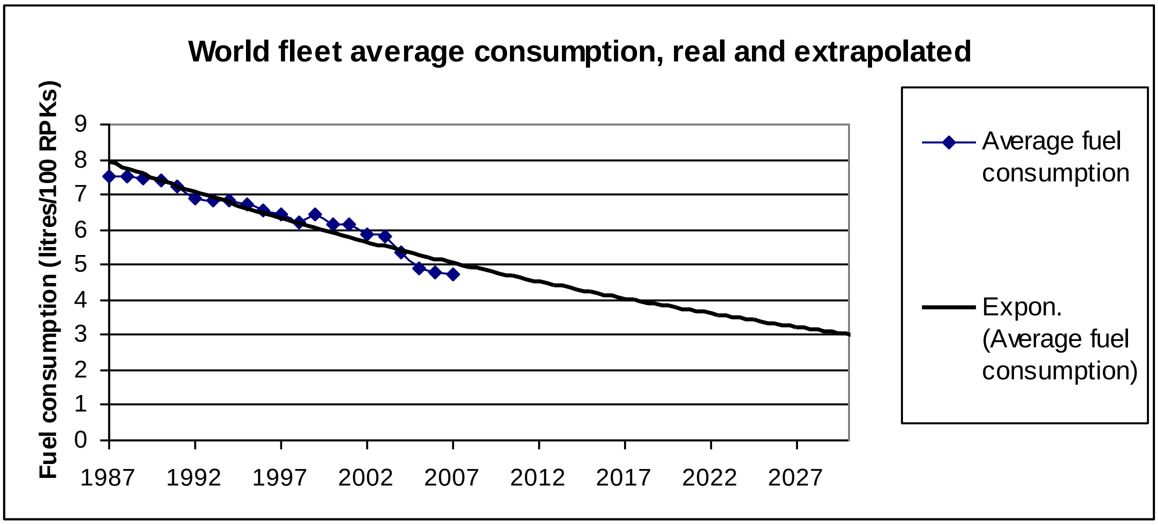

Figure 18: The world fleet of aircrafts average fuel consumption extrapolated with an exponential trend line to predict possible fuel consumption in the future. Source: Airbus 2007.

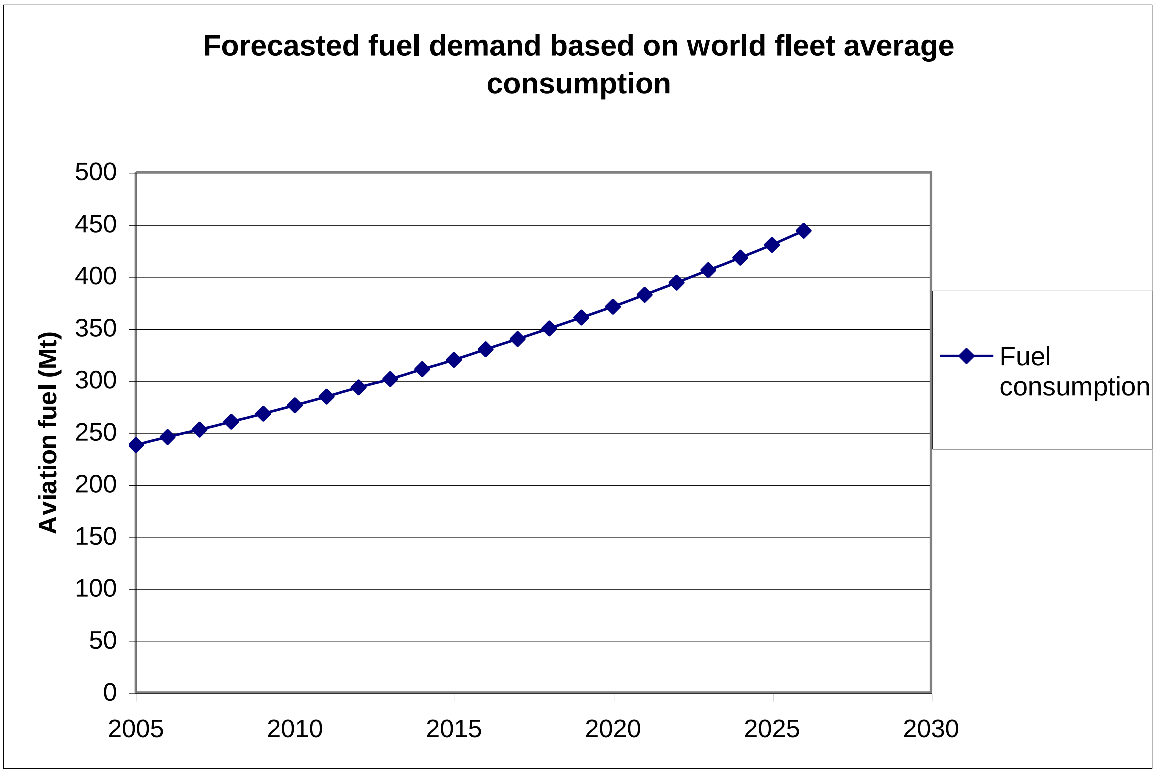

Figure 19: Outlook on aviation fuel demand, with 5 per cent traffic growth and extrapolated fuel efficiency increase. Source: Data from SIKA-institute 2008, Boeing 2007 and Airbus 2007.

Figure 19 shows the forecast for aviation fuel demand for Scenario D. The increase in aviation fuel demand will be about 3 per cent a year. This result is similar to Scenario C, the orange curve of Figure 15.

This forecast of aviation fuel demand is also compared to the peak oil production scenarios 1, 2 and 3 (Figure 20 and 21).

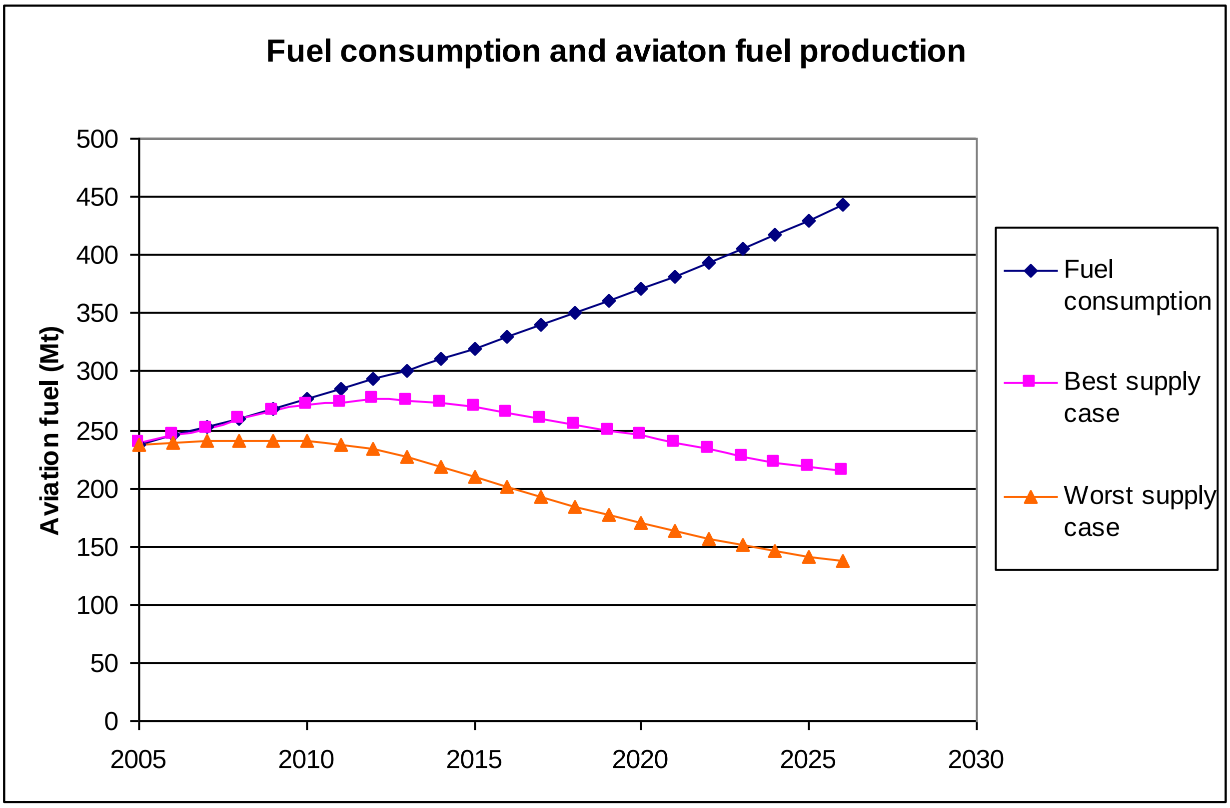

Figure 20: The forecasted jet fuel consumption of Figure 18 together with the best case and the worst case of Robelius peak oil scenario (Scenario 2 and 3). Source: Data from Airbus 2007, IEA 2007, SIKA-institute 2008 and Robelius 2007.

The result is similar to Figure 16, the difference between the forecast for fuel demand and the forecast for available aviation fuel in 2026 is large.

For comment on Figure 20 see 12.2.

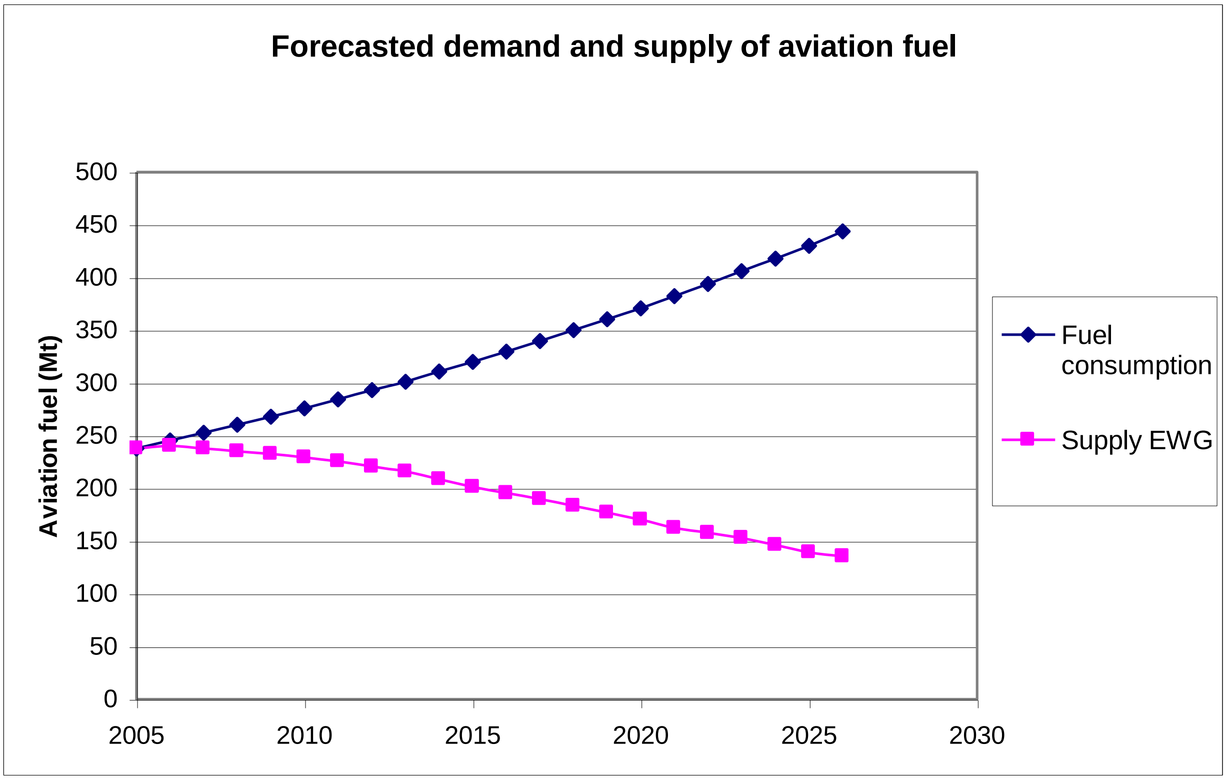

Figure 21: The forecasted fuel efficiency together with traffic data and traffic growth compared with the Energy Watch Group peak oil forecast. Source: Data from EWG 2007, Boeing 2007 and SIKA-institute 2008.

Figure 21 shows aviation fuel consumption Scenario D compared to aviation fuel production Scenario 1 (see chapter 11.1 and 11.3). The supply case of EWG is similar to the worst supply case of Robelius.

According to this results there would be a growing problem of provision of fuel for the world fleet of aeroplanes if crude oil production peaks, even if aviation traffic remain as it is today.

For comment on Figure 21 see 12.2.

13 Discussion

The lack of aviation fuel that is forecast in this report is fixed to one given situation, aviation traffic growth of 5 per cent a year and aviation fuel as 6.3 per cent of refinery products. It is also assumed that world oil production will decrease.

A decreasing crude oil production would also affect the availability of other fuels and the global economy. That can have an effect upon demand for air travel and transportation can be less than predicted.

The relationship between different refinery products can be changed to some extent. This gets us back to the discussion about what is more important for civilisation in the future. Is it flying for the annual vacation or ploughing the fields for food? Ground based vehicles could easier change their fuel to biofuels or could even be electrified, if this is done maybe it would be possible to increase jet fuel production from crude oil for a while.

Consumption of crude oil products such as jet fuel are predicted to keep increasing without taking into account possible crude oil production. If this is done it can be seen that it will be difficult to produce the amount of jet fuel needed.

13.1 Aviation fuel can be a larger part of refinery production

The yield of different fuels from the refinery is in reality no fixed number. It is dependent on demand, crude oil quality and refinery capacity. Within this field there is a great amount of work to be done to understand the future capacity of different crude oil products. Today it is possible for jet fuel to be a larger part of refinery output but refineries are trying to be as profitable as possible and their production is dependent upon the grade of crude oil to be refined.

The maximal output of fuels may not match market demand. A change in demand for diesel fuel has led to diesel prices increasing at a rate above gasoline prices, taking jet fuel prices up as well. Aviation fuel can be a larger part than 6.3 per cent of the refinery production but the production of diesel will then, by necessity, be lower.

Crude oil with a high API grading that is low on sulphur and other contaminants is easiest to extract, transport and refine. This crude oil was the first to be extracted. The qualities of today’s crude oil require more processing in the refineries and it is more complicated to produce, leading to higher costs for both production and processing.

Forecasting future fuel production without taking into account either the grade of crude oil or the refinery capacity gives a somewhat misleading picture of available fuel. A full evaluation of all factors is a demanding task, beyond the scope of this report.

14 Conclusions

In this report it has been found that aviation traffic will not be able to grow after crude oil production peaks. If aviation fuel is assumed to be a fixed part of refinery output then aviation fuel production will fall below current consumption levels. Increasing the aviation fuel part of refinery output is possible but affects the production of other fuels. The competition with diesel fuel production will probably increase.

The growth of aviation traffic is not entirely correlated to aviation fuel consumption since new, better aeroplanes enter the market, new routing and traffic control makes the journey shorter and the fuel consumption less. However, these projected fuel efficiency increases cannot keep the level of aviation fuel consumption as it is today or lower it, if air traffic increases as predicted.

Biofuels will most likely not be able to replace jet fuel for the aviation industry in the near future, but can be important in the far future. Alternative fuels produced from coal is in the near future the most probable alternative fuel to replace some conventional jet fuel.

Aviation is important and will probably continue to exist in the future, but possibly with less frequent traffic than we see today.

Further research

Working on this report it has been noted that two interesting areas for further research have appeared:

- Investigation of the connection between crude oil quality, refinery capacity and future jet fuel production.

- Investigation of what the maximal aviation fuel production could be, with no respect to producing other fuels.

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