Bio Jet Fuel from Macro Algae

A feasibility study into the end-to-end chain

Thesis

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February, 2010

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Challenge the future

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Summary

Biofuels are essential for the future of aviation. The airline industry is a worldwide operating business to transport passengers and freight in an economical and fast manner. Jet engines consume kerosene to power the aircraft. However, kerosene is a distillate of crude oil and airlines are entirely dependent on this energy source. As a result, airlines are facing two problems. Firstly, the energy security is at stake when the conventional oil resources are depleted. Secondly, green house gases are produced by burning fossil fuels. Carbon dioxide is one of them and it is regarded by scientists as contributor to climate change (IPCC fourth assessment report group I, 2007). Biofuels solve these two issues, as they are renewable and they emit less carbon dioxide.

Several airlines have already conducted test flights with biofuels, such as Virgin Atlantic, Air New Zeeland, Japan Air Lines and KLM. Feedstocks for these biofuels were camelina, jatropha and micro algae. Macro algae are also a feedstock for biofuels. This report is dedicated to the feasibility of bio jet fuel from macro algae from an end-to-end chain perspective. The main research fields were on the technical side, sustainability side and economical side of the bio jet fuel.

Technically, it is possible to produce bio jet fuel from macro algae. Several macro algae cultivation methods and conversion methods exists to produce bio jet fuel. It is also better for the environment. The carbon dioxide emissions are reduced at least with 75% compare to fossil fuels. Besides this, the energy balance is also positive. More energy is produced in the form of biofuel than the energy is needed to produce it. An issue so far is the economical side of bio jet fuel. Bio jet fuel is substantially more expensive than fossil fuels. The price will decline when the production of macro algae increase. The transition from fossil fuels to biofuels will take decades and large investments are essential. In this report, several actions are discussed how the transition to bio jet fuels can be accelerated.

List of contents

Acronyms

ASTM	American Society for Testing and Materials
ATAG	Air Transport Action Group
CEO	Chief Executive Officer
CO_2	Carbon dioxide
CSR	Corporate Social Responsibility
DAF	Dry Ash Free
DAFMT	Dry Ash Free Metric Tons
EC	European Commission
EIA	Energy Information Administration
EROEI	Energy Returned On Energy Invested
EU ETS	European Union European Trading Scheme
FAME	Fatty Acid Methyl Esther
FAO	Fisheries and Agricultural Organization
FT	Fischer Tropsch
HDO	Hydro De Oxygenation
HHV	Higher heating value
HRJ	Hydro Renewable Jet
HTU	High Thermal Upgrading
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
KLM	Koninklijke Luchtvaart Maatschappij
LHV	Lower heating value
MOD	Ministry Of Defense
PPO	Pure Plant Oil
PR	Progression Ratio
UK	United Kingdom
UNFCCC	United Nations Framework Convention on Climate Change
USA	United States of America

Symbols, units and conversion factors

Symbols

$	US Dollar
€	Euro
bbl	barrel

Units

EJ	Exa Joule	10^{18} J
GJ	Giga Joule	10^{9} J
ha	hectare	10^{4} m^2
kg	kilogram	
km^2	Square kilometer	
m^2	Square meter	
m^3	Cubic meter	
MJ	Mega Joule	10^{6} J
MW	Mega Watt	10^{6} W
PJ	Peta Joule	10^{15} J
W	Watt	
wt	weight	
yr	year	

Conversion factors

Crude oil	7.33 bbl/ton
Dollar/Euro	1.4 $/€
Jet fuel	7.8 bbl/ton

1 Introduction

The aviation industry is a mature form of transport where passengers and freight are transported globally (ATAG, 2009). Jet fuel is a distillate from fossil fuel and it is the common energy source to power aircraft. As a result, the aviation industry fully relies on fossil fuels. The energy security is at stake when the conventional oil resources are depleted. Besides this, fossil fuels produce the greenhouse gas carbon dioxide. Carbon dioxide is regarded by scientists as contributor to climate change (IPCC fourth assessment report group I, 2007). An alternative renewable energy is needed to solve these issues in energy security and global warming. Biofuels are a key element and are the alternative renewable jet fuel. Several test flights powered by a blend of biofuel and traditional jet fuel have already been performed. Feedstocks for these biofuels were camelina, jatropha and algae. Another feedstock might be macro algae. From this background information, the research question is defined as:

Is it feasible to produce bio jet fuel from macro algae in a sustainable and economical manner from an end-to-end chain perspective?

The aviation industry has been working to a more sustainable operation for years (IPCC fourth assessment report group III, 2007) mainly by reducing fuel consumption. Firstly, more background information is discussed how fuel consumption per passenger kilometre evolved over the years. However, decreasing fuel consumption is not solving the energy security. Airlines are facing this problem and have been looking to alternative fuels in the last few years. As a result, small quantities of bio jet fuels have been produced and tested. This background information is discussed in section 2. From this background information is defined the main research question. A research method to answer this research question is mentioned in section 3.

Three main processes are needed until the airline can take delivery of the bio jet fuel, namely: production of biomass, conversion into bio jet fuel and finally distribution and delivery. This is also called the end-to-end chain. Several methods exist to cultivate and convert macro algae into bio jet fuel. Trade-offs are performed which method suits the best and as a result, the end-to-end chain is defined. It appeared that, technologically, it is not a problem to produce bio jet fuel. The analysis of the end-to-end chain is discussed in section 4. The feasibility can be determined from this point and will be discussed in section 5. The end-to-end chain is analysed if it is feasible to produce bio jet fuel in a sustainable and economical manner. The terms ‘sustainable’ and ‘economical’ are defined in the research method. It appeared that the carbon dioxide emission of bio jet fuel compared to fossil fuels will drop at least 75% if all CO_2 is absorbed by the oceans again. A problem is to produce it in a manner that is economically competitive to fossil fuels. The cost price will drop significantly when production starts and an impulse in investments is necessary to get it rolling. Finally, in section 6 the conclusions and recommendations are drawn.

2 Background information

Since the first successful powered flight performed by the Wright brothers in 1903, aviation has evolved to a mature form of transport. Although the outer design of the aircraft has not changed significantly since the introduction of a jet powered passenger aircraft, new and improved technologies have contributed to reduced fuel consumption and emissions. New technologies developed rapidly and aircraft evolved into an efficient, rapid, affordable and reliable form of transport. Currently, 2.2 billion passengers are moved by aviation annually. Aviation provides more than 32 million jobs worldwide and is responsible for 7.5% of the global gross domestic product (ATAG, 2009).

Currently, aircraft are powered mainly by fossil fuel, which is a distillate from crude oil. 241 million tons of jet fuel was consumed in 2007 (IEA, 2009). The end-to-end chain of fossil fuels is described in Appendix 1. Mankind is facing two problems with regard to the consumption of fossil fuels. Firstly, fossil fuels are depleting and secondly, green house gases such as carbon dioxide (CO_2), nitrogen oxides (NO_x) and contrails are produced when fuels are burned. Greenhouse gases are regarded by scientists as contributor to climate change (IPCC fourth assessment report group I, 2007). The radiative forcing from aircraft caused by green house gases are visible in Figure 1 and the contribution of carbon dioxide is substantial.

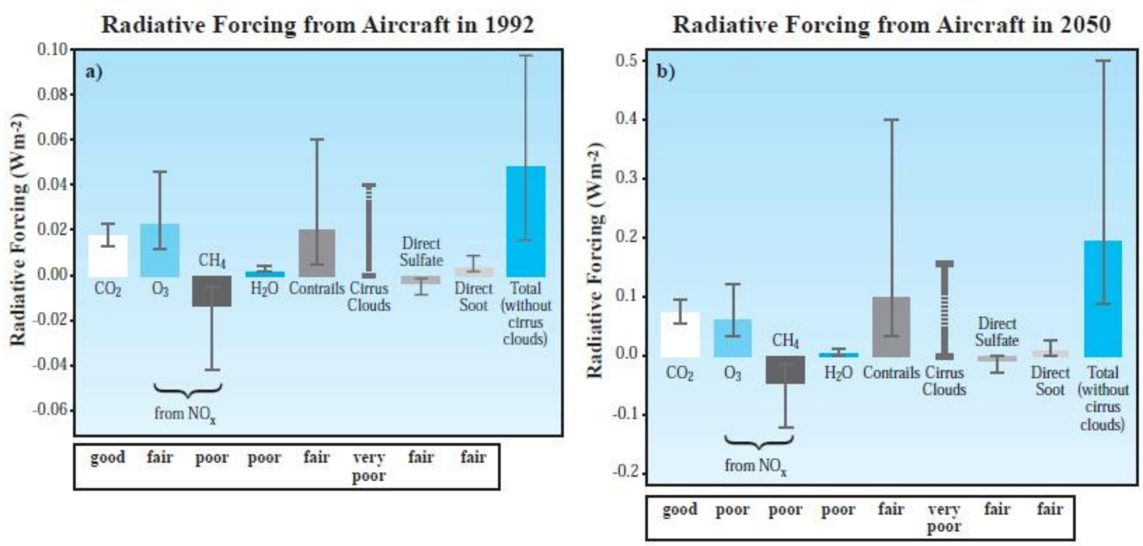

Figure 1 Radiative forcing from aircraft (IPCC, 1999)

Global crude oil production can be considered as a technical system, which implies that the life cycle of the production of crude oil can be described by an 's-curve'. The curve shows the main characteristics of the system changes over time (Eversheim, 2003). The four characteristics of the s-curve are: introduction, growth, maturity and decline. New innovative technical systems should be introduced in the maturity phase. The growth phase of the successor starts when decline has started of the predecessor technical system. See Figure 2 for a schematic view of the s-curves of oil production and biofuel production. The introduction of biofuel should happen when the maturity phase of oil production has been reached.

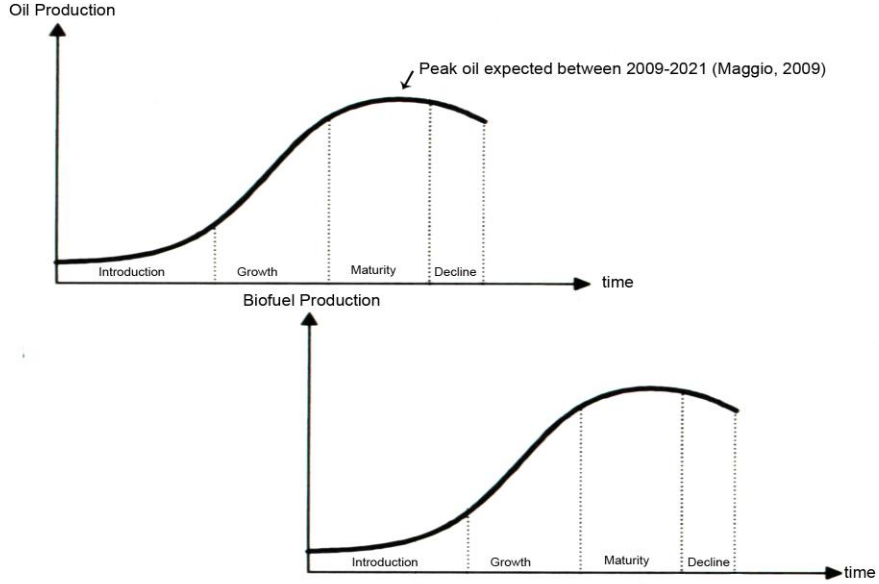

Figure 2 Innovation curve (Eversheim, 2003).

In Figure 3, the global conventional oil discoveries and oil production rates are given. The grey columns are the oil discoveries and the yellow columns are the forecasted oil discoveries. These are summed up in the pink line. The yellow dots are the annual oil production rates and these are summed up in the blue line. The oil production is forecasted to increase according to the red dots. The difference between the pink and blue line are the global reserves. This gap is getting smaller, because new oil fields are not discovered. In this scenario, all conventional oils are consumed by 2035.

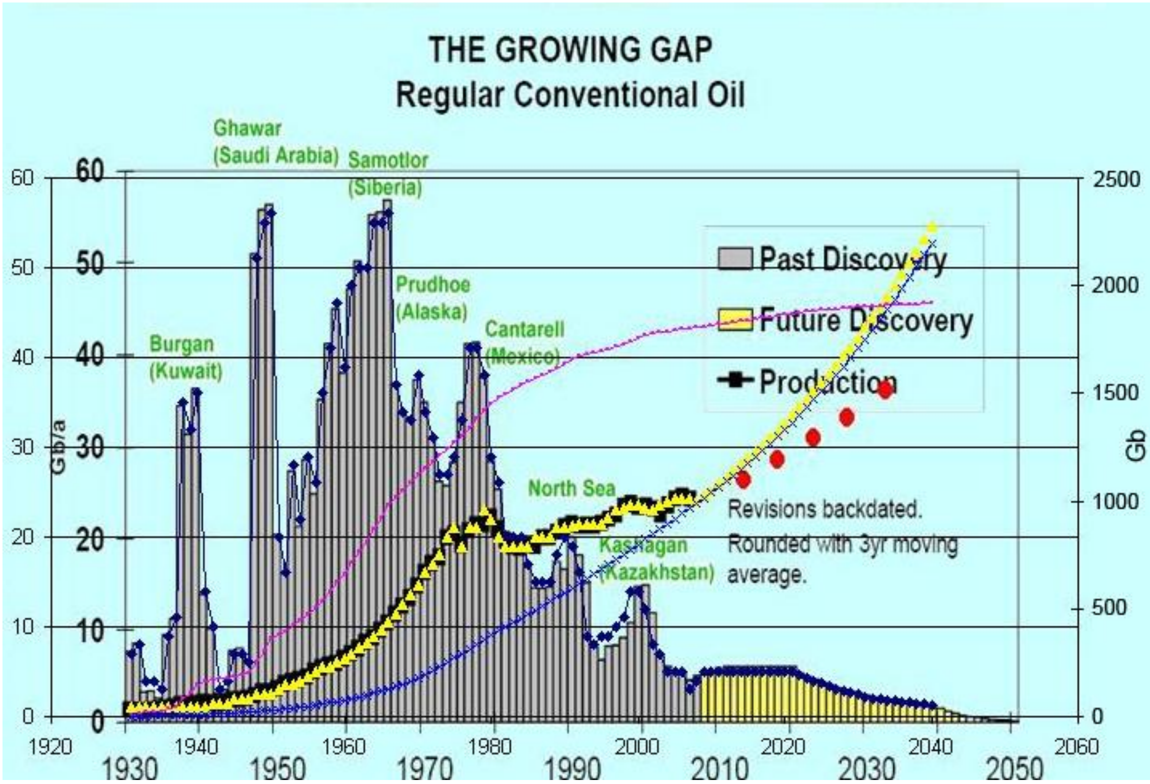

Figure 3 The global discovery and production of regular conventional oil. The pink line is the cumulative oil discovery and the blue line the cumulative produced oil. These lines are crossing in 2035 which means, the regular conventional oil is depleted by 2035.

Aircraft become more fuel-efficient every year. Figure 4 shows the evolution in aviation fuel consumption per passenger kilometre (pk). In this index, year 2000 is set to 100. Fuel consumption is forecasted to reduce by 50 percent in 2050. Interestingly, fuel consumption is directly related to carbon dioxide emissions. Air transport is currently responsible for two percent of man-made carbon dioxide emissions (IPCC aviation and the global atmosphere, 1999). IPCC projected six different scenarios how carbon dioxide emissions will grow depending on industry growth and developments in reduced fuel consumption. Carbon dioxide emissions from air transport are forecasted to rise to three percent of man-made emissions by 2050 (IPCC aviation and the global atmosphere, 1999). This is based on the reference scenario Fa1 (Figure 5) with the assumption air traffic will grow with 3.1% a year and carbon dioxide emissions will grow with 1.7% per year.

IATA brought the aviation industry's environmental goals to Copenhagen where the climate summit took place in December 2009. Airlines, airports, air navigation service providers and manufacturers are calling for a global approach to reduce aviation emissions and are united in a commitment: to improve fuel efficiency by an average of 1.5% per year to 2020; to stabilize carbon emission from 2020 with carbon-neutral growth; and to realize a net reduction in carbon emissions of 50% by 2050 compared to 2005 (IATA press release no.: 54, 2009)

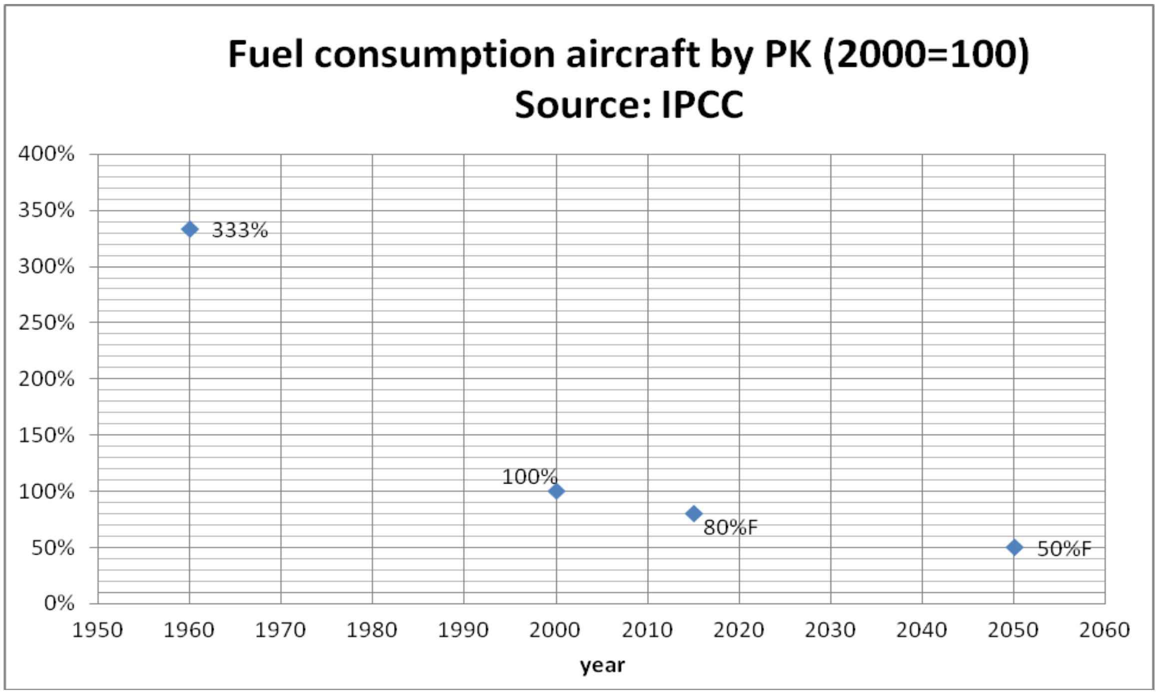

Figure 4 Index aviation fuel consumption evolution per passenger-km (pk), year 2000=100 (IPCC aviation and the global atmosphere, 1999). The fuel consumption per pk declined with 70% in the time frame 1960-2000. It is forecasted that next generation aircraft consume 20% less fuel in 2020 and 50% in 2050.

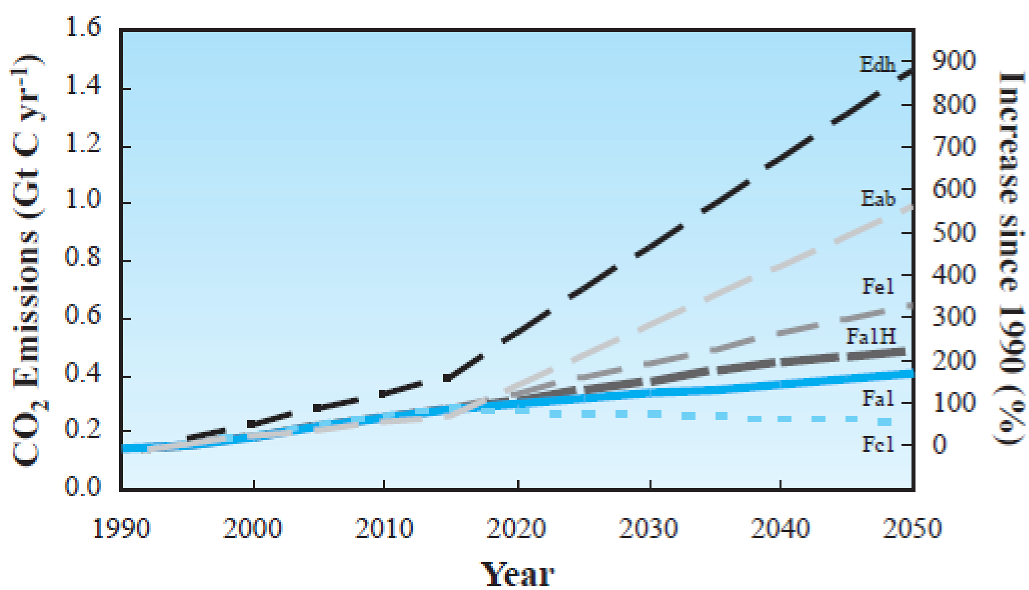

Figure 5 Total aviation carbon dioxide emissions resulting from six different scenarios for aircraft fuel use (IPCC aviation and the global atmosphere, 1999). Most likely scenario is scenario Fa1. Air traffic grows 3.1% annually and emissions grow 1.7% annually.

"The aviation industry is already working towards its climate change goals through its four pillar strategy. The strategy focuses on investing in new technology, flying smarter, building efficient infrastructure and taking advantage of positive economic measures" according to Giovanni Bisignani, IATA's Director General and CEO, as he presented to the United Nations Framework Convention on Climate Change (UNFCCC) in Copenhagen (IATA press release no.:54, 2009). Several programs which are running currently to reduce fuel consumption:

- Original equipment manufacturers (OEM): aircraft engines become more fuel efficient and aircraft manufacturers make use of new innovative technologies to reduce weight and fuel consumption (IPCC aviation and the global atmosphere, 1999, Figure 4).
- Airlines: reduce fuel consumption during operation. For example, KLM launched a weight & fuel plan in fall 2008 and set a target of reducing emissions by 1% yearly. This plan has four pillars: optimizing airspace, weight reduction, adjusting fuel loads and optimizing flight procedures (Air France- KLM CSR Report, 2009).
- Politics: are working on a Single European Sky. On average, aircraft fly 49 km longer than strictly necessary due to airspace fragmentation. Total fuel savings can be up to 7-11% if a single European sky is implemented (Commission of the European Communities, 2008). The European Union is working on greenhouse gas trading scheme. In January 2005, the European Union Greenhouse Gas Emission Trading System (EU ETS) commenced operation as the largest multi-country, multi-sector Greenhouse Gas Emission Trading System worldwide. EU ETS will be effective for the aviation industry in 2012 (official journal of the European Union, decision 2009/339/EC).

The aim of these programs is to reduce green house gas emissions in aviation. All ongoing developments are focused on reduced fuel consumption. So far, aircraft remain being propelled by fossil fuels. However, the aviation industry could reduce more carbon dioxide and become fossil fuel independent when biofuels are used. This is visualized in Figure 6, the life cycle of fossil fuel and biofuel are given. The carbon dioxide is absorbed by biomass and is emitted again when the biofuels are burned. Besides that, biofuel is also a renewable energy, because the natural process of crude oil production is speeded up. As a result, the aviation industry is not dependent on fossil fuels anymore. Therefore, research is going on into biofuels as replacement of fossil fuels.

Several test-flights are already performed in 2008-2009 by several airlines. Virgin Atlantic, Air New Zealand, Japan Air Lines, Continental Airlines used a blend of jet fuel and biofuel. The feedstocks for these biofuels were: camelina, jatropha, coconut and micro algae. KLM performed the first flight with passengers onboard powered by a blend of camelina biofuel and jet A-1 (KLM press release, 2009). Interests in energy from algae are growing when energy prices are rising and the potential of algae is massive (Bird, 1987). If all aviation fuels from fossils are replaced by biofuel made of algae, a landmass of Belgium is required for algae cultivation according to Boeing (Paisly, 2008) and ATAG (2008). Algae can be divided into micro algae and macro algae (also named kelp or seaweed). Both groups contain energy in the form of proteins, lipids and carbohydrates. These can be converted into biofuel. Currently, much research is going on to biofuel from micro algae (Shell, ExxonMobil). A couple of Dutch companies (Ingrepro, Lgem) cultivate micro algae for different purposes. However, a

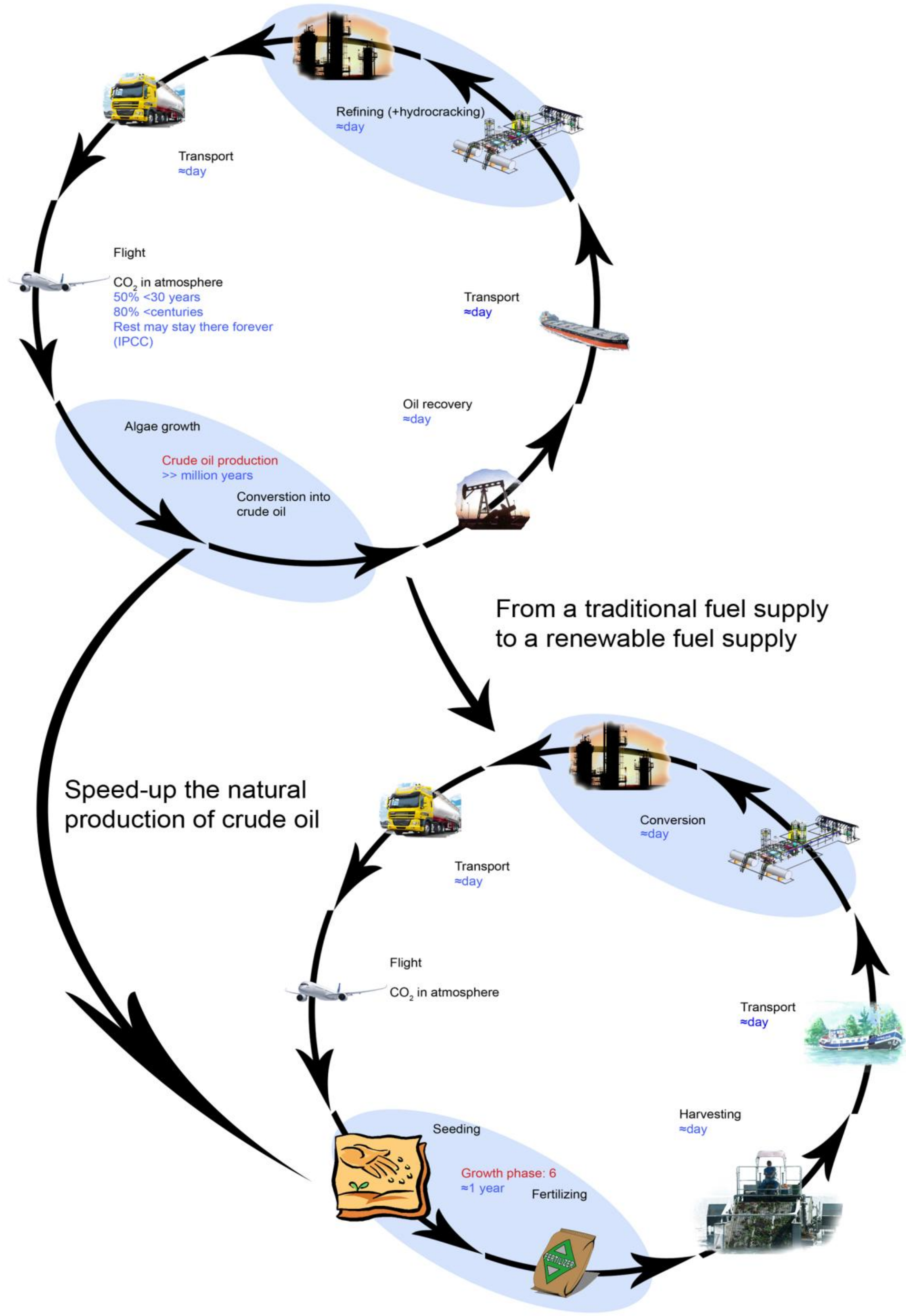

Figure 6 Life cycle of crude oil (upper) and the life cycle of biofuel (lower) which is renewable.

problem with micro algae is the energy balance as was reported by several scientific papers. Biodiesel from micro algae has an energy returned on energy invested (EROEI) of (-0.6)-0.9 (Lardon, 2009). The biodiesel, which is a fatty acid methyl ester (FAME), does not meet specifications of jet fuel. Therefore, an upgrade (hydrotreatment) is necessary which is unfavourable to the energy balance. Barbosa (2008) reports an EROEI of (-0.5)-1 only for microalgae production. According to Lgem, a micro algae producer in the Netherlands, it is possible to produce micro algae with an EROEI of 0.25 at maximum (Roebroeck, 2008). Conversion to biofuel lowers EROEI and will result in a net energy production of less than zero or close to zero. Energy production requires an EROEI of >0. Currently, of all biofuels, Brazilian ethanol from sugarcane has the highest EROEI, which is 7 (Pereira, 2010). Hydro renewable jet (HRJ) from macro algae has a larger EROEI than micro algae (Bird, 1987). From this point of view, macro algae are a better feedstock unless a breakthrough that will improve the EROEI of micro algae.

Research Question

The aviation sector is leaning towards a sustainable industry. Biofuels are a key element in this development to tackle issues about depleted energy resources and CO_2 reduction. However, biofuels from macro algae have not been investigated yet. As a result from the background information, the research question is defined as:

Is it feasible to produce bio jet fuel from macro algae in a sustainable and economical manner from an end-to-end chain perspective?

Sustainable development is defined according tot the IPCC: “Development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. In other words, “the ability for resources to be used in such a way so as not to be depleted. For humans to live sustainably, the earth’s resources must be used at a rate at which they can be replenished, providing economic growth and social development to meet the needs of today without compromising the needs of tomorrow” (ATAG, 2009).

‘Feasible’ is defined in this research question as:

- Renewable and sustainable production of all demanded aviation fuel.
- A positive energy balance in the end-to-end chain (EROEI>4).
- Reduced carbon dioxide emissions in the end-to-end chain (>75%).
- Economical viable.

3 Research method

The main research question originated from the background information and was discussed in the previous section. The feasibility of bio jet fuel from macro algae is determined by the perspective of end-to-end chain, which has not been defined yet. The feedstock and end-product are known, namely, macro algae and jet fuel, respectively. However, the cultivation and conversion method need to be determined. The last step is distribution. These three processes form the end-to-end chain, see Figure 7.

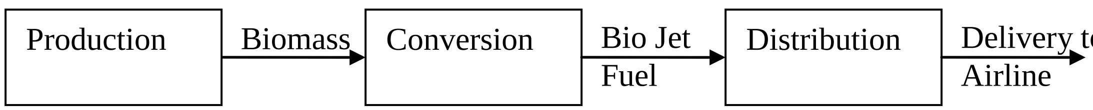

Figure 7 End-to-end chain for bio jet fuel from macro algae.

As already said, the production and conversion method need to be determined. Several macro algae cultivation systems exists and four of them will be explained. A trade-off between those four will determine which one suits the best. This trade-off is performed according to four criteria: capacity, sizing and economics. The reason is per criteria:

- Capacity: yields are compared for efficient cultivation.
- Sizing: The area needed to cultivate macro algae to fulfil jet fuel demand.
- Economics: the cost price should be economical competitive with global market fuel prices in the long term.

The second process in the end-to-end chain is conversion. In this process, the biomass is converted into bio jet fuel. Several conversion routes exist and the feedstock and fuel which is produced are of importance. All conversion routes are reported and analysed on feedstock and product. The ones that fulfil both requirements are taken to a trade-off, based on these criteria:

- Wet/ dry supply: macro algae are wet supplied and if drying is necessary, an extra treatment is required. Energy is required for drying and is unfavourable for the energy balance.
- Capacity: demand from airlines must be fulfilled and conversion plants must have the capacity to fulfil this demand.
- Economy: conversion plants must be economically competitive with global market fuel prices in the long term.
- Carbon dioxide balance: CO_2 emissions must meet the requirement to reduce emissions in the end-to-end chain.
- Energy balance: the energy balance in the end-to-end chain must be positive.

After both trade-offs, the end-to-end chain is defined and can be analysed on feasibility. As already explained in the introduction, feasibility is defined by four criteria. Firstly, the macro algae production should be renewable and sustainable. Secondly, the energy balance should be larger than four and preferably better than other feedstocks for biofuels. The energy produced in the form of bio jet fuel is divided by the summation of energy consumed in each process. Thirdly, the carbon dioxide emission in the life-cycle of bio fuel should be reduced at least 75% compare to the emissions of fossil fuel. The carbon dioxide emissions in each process are summed up and compared to the emissions of fossil fuels. Finally, the bio jet fuel should be economical viable. The cost-price of bio jet fuel is determined by a hybrid approach. In the first approach, the cost price of bio jet fuel is determined by experience curves. In the second approach, the cost price is calculated in each process and summed up. Both approaches will complement each other, hopefully. The bio jet fuel is economical viable if users demand this fuel at the requested price. Demand could be created by passengers, defence, or legislation in promoting these fuels. These actions are discussed further. In the end is concluded if bio jet fuel from macro algae is "feasible".

4 Analysis the of end-to-end chain

The end-to-end chain is analysed in this section. As already said, the supply chain consists of three main processes, namely: production of biomass, conversion into bio jet fuel and finally distribution to the airline, see also Figure 8. The distribution process of bio jet fuel does not change from the distribution of fossil fuel. The production and conversion processes needs to be determined. A trade-off between several production and conversion processes is performed. The combination production and conversion leads to a quality bio jet fuel. The quality of the bio jet fuel is determined firstly. As a result, the conversion and production process can be determined.

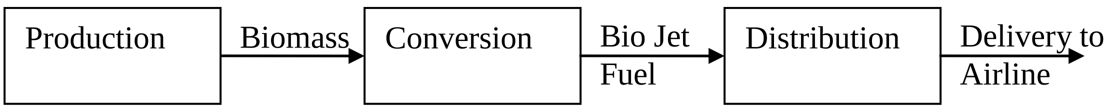

Figure 8 End-to-end chain bio jet fuel from macro algae.

4.1 End product

Aviation fuel (jet A-1 or jet A) is a mixture of hydrocarbons. Each component has its own characteristics and these combined give the characteristics to the aviation fuel. Two regulators made specifications for aviation fuel over the years. The fuel is certified and has to meet these requirements. The composition of jet A-1 is discussed firstly. Secondly, a summary about aviation fuel specifications is given.

Fuel composition
The composition of fuel is described to get more insight in the chemical structure of jet fuels. The fuels are a mixture of hydrocarbons divided into four groups: n-parrafins, iso-paraffins, naphthenes and aromatics. These groups are described according to Snijders (2009).

N-paraffins are saturated, straight chain hydrocarbons. All carbon atoms are connected in a single chain without any double bonds between the carbon atoms. The general formula of the paraffins is C_nH_{2n+2}. These chains contain relative many high-energy hydrogen-carbon bonds. The simplicity results in a relative low boiling point and high heating value. Bacteria like these paraffins, which could lead to bacteria colonies in fuel tanks – a possible disadvantage. Iso-paraffins are isomers of n-paraffins. The formula remains the same as n-paraffins, C_nH_{2n+2} and the heating value per unit mass is about the same. The difference is that the atoms are not ordered in a single chain and the molecules are not stacked as close as n-paraffins. This could lead to a lower density and volumetric heating value. The boiling point and freezing point are lower compare to n- paraffins. See Figure 9 for the chemical structure of pentane and isopentane.

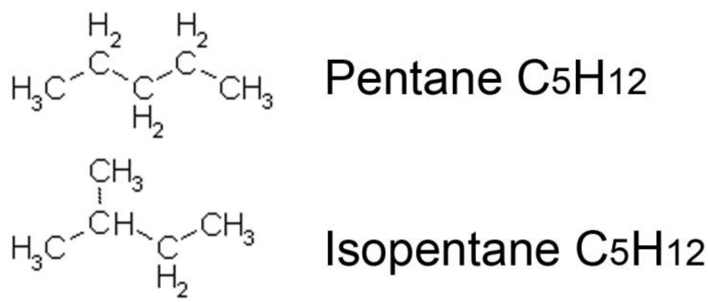

Figure 9 Structure pentane and isopentane. Pentane is formed by a single chain of carbon atoms. Isopentane is not formed in a single chain. Both have an equal chemical formula.

Naphthene molecules are formed by a single chain of carbon atoms in a ring shape and do not have double bonds between the carbon atoms, see Figure 10. The formula is C_nH_{2n}. The two missing hydrogen molecules compared to paraffins give a lower gravimetric heating value. The density and volumetric heating value are higher. The freezing point is lower due to the irregular shape. The boiling point is about the same as paraffins.

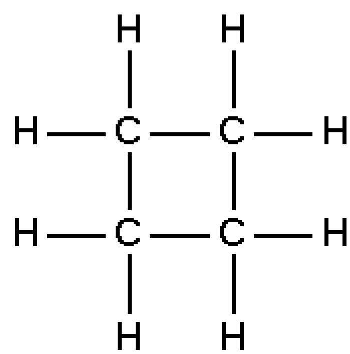

Figure 10 Cyclobutane, formed by a single chain of carbon atoms in a ring shape.

Aromatics are hydrocarbons with one or more benzene rings. These rings consist of six carbon atoms and double bonds exist within the rings, see Figure 11 for the chemical structure. Aromatics have a higher density than naphthenes and a lower gravimetric heating value due to fewer hydrogen carbon bonds. The volumetric heating value, boiling point and freezing point are higher than naphthenes or paraffins. Aromatics have a complex structure, which affects combustion and leads to more unburned hydrocarbons and soot emissions. A low aromatic content is preferred. On the other hand, aromatics are required for lubrication and O-ring swelling.

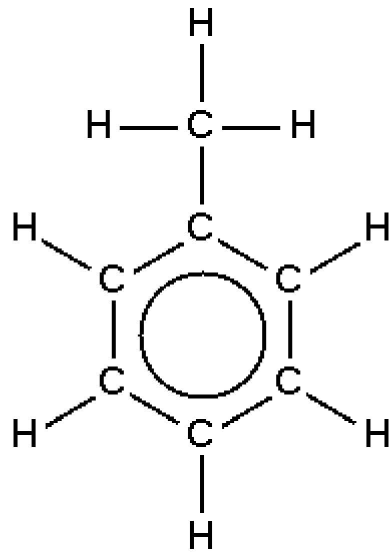

Figure 11 Toluene, a carbon chain attached to a benzene ring.

Specifications

Aircraft operate in extreme conditions, just to mention the temperature or static pressure. Therefore, aviation fuels should be able to handle these conditions. A list of specifications has been set up which fuel has to fulfil. These specifications are set up by American Society for Testing and Materials (ASTM) and the UK Ministry of Defence (MOD). In this section, specifications are summarized. The data is obtained from Snijders (2009).

- Solid matter or water in the fuel can cause problems in the fuel system and engine. Solid particles can block lines, filters or valves and lead to increased fuel system wear and soot formation. A maximum particulate contamination of 1.0 mg/l is allowed. Water can evaporate or freeze and block fuel lines. Water is separated from fuel and sinks, because water is heavier than fuel. The lowest points in the fuel tanks must be checked regularly for water contamination.
- The composition of the fuel is important. The presence of acids can lead to corrosion and attracts water. Therefore, a maximum acidity is set and measured in potassium hydroxide concentration equivalent. The amount of aromatics is limited to 25% of the volume. A higher concentration can lead to more air pollution and affects combustion efficiency. Sulphur leads to more air pollution and this is restricted to 0.3% of the fuel mass. The percentage of hydro processed fuel must be reported. Unsaturated species are reduced by adding hydrogen atoms in this process. This leads to fewer lubricants in the fuel and a lubricant should be added.
- 10% of the fuel must be evaporated and recovered at the condenser at a maximum temperature of 205 ºC. This distillation range gives an indication of the composition of the fuel. The fuel is evaporated and led to a condenser with a temperature between 0 and 4 ºC. The fuel is fully evaporated at 300 ºC and a maximum of 1.5% of the volume may be left over. Both tests show that the fuel

does not contain large molecules that result in inefficient combustion, more soot and unburned hydrocarbons. At the end of the distillation process, at least 98.5% of the volume must be recovered.

- A minimum flash point is set at 38 ºC. This is a compromise between the flammability characteristics and the safety of fuel storage. A lower flash point means the fuel is easier to ignite especially at lower temperatures. For safety reasons a high flash point is desirable, as flammability mixtures must be avoided.
- The fuel density must be between 775 and 840 kg/m^3. The lower limit is set to meet the energy payload-range performance and aircraft are structurally designed for the upper limit.
- The freezing point of the fuel must be below -47 ºC. When the fuel freezes, the viscosity of the fuel becomes too high and it will not flow anymore.
- Minimum energy content is set at 42.8 MJ/kg fuel. Together with the fuel, density ensures the payload-range of the aircraft. A maximum is not set, because higher energy content improves the payload-range performance.
- The smoke point flame length should be between 19-25 mm together with a maximum of 3% of the fuel volume of naphthalene. A longer flame is cooler and will not burn completely and this produces smoke. A shorter flame length where smoke is produced means a dirtier fuel.
- High temperatures in the engine could lead to coking and deposition of solids in the fuel lines and nozzles and can influence the flow. The fuel stability is checked by flowing it through a tube at 260 ºC. A filter is installed in the fuel flow to check it for increased viscosity or depositions. The pressure differential must not exceed 25 mm Hg.
- An extra check is performed on the volatility of the fuel and presence of large molecules. Hot air or steam is led through the fuel which will evaporate. The remaining material called gum must not exceed 7 mg per 100 ml of fuel.
- The conductivity must be between 50-450 pS/m. A minimum is set to avoid static charging during refuelling and a maximum is set to avoid electric currents flowing through complete fuel systems.
- Fuel is used for lubrication as well. In hydro-processed fuels, these lubricants are removed. The wear scar diameter must be tested for fuels containing more than 95% hydro processed fuel.
- Jet fuel is used for oil cooling in airlines. Jet A-1 has a heat capacity of around 2000 J/kgK at 15 ºC. A fuel with lower heat capacity could be critical.
- The fuel must not harm any of the components and parts that are in contact. All parts are designed such that they will work well with Jet A-1. The harmfulness of an alternative fuel must be investigated.
- Another positive effect of fuel on materials is the O-ring swell. When an O-ring comes in contact with fuel, the O-ring will swell. Alternative fuels could have no effect or even a shrinking effect and leakages occur. This must be investigated.

Bio jet fuel

The list of specifications for Jet A-1 is given. The bio jet fuel should be a mixture of iso and N-paraffins, preferably. Besides this, a quantity of aromatics is required for lubricant. It could be that not all specifications are fulfilled for bio jet fuel. However, some specifications are always required. The essential requirements of bio jet fuel are according to BP (Clark, 2008) and Boeing (Paisly, 2008):

- Maintain performance over wide temperature range -50<T (ºC)<+40.
- Maintain performance over wide pressure range 0.3< P (atm) <1.
- Have agreed and controlled specification for engine/aircraft production.
- Offer good energy content per unit weight.
- Permit easy handling and storage.
- Be readily available on a global scale.
- Be cost competitive to fossil fuels.

Several conversion routes from biomass to alternative fuel exist. Hamelinck (2006) gave an overview of these routes, see Figure 12. Macro algae belong to the lignocellulosic biomass. Each conversion route produces a different fuel type.

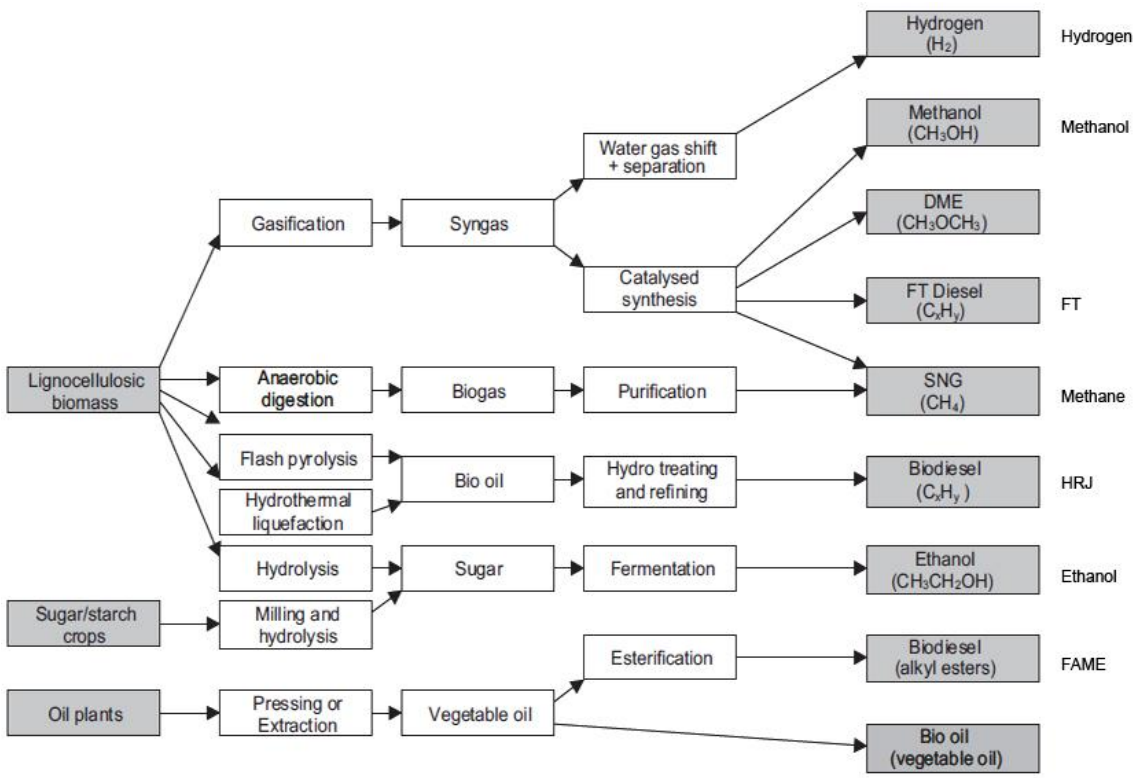

Figure 12 conversion routes from biomass to liquid fuels (Hamelinck, 2006).

Eight of these fuel types are discussed for energy content and energy density. These fuel types are: Fischer-Tropsch (FT) fuel, hydrotreated renewable jet (HRJ), liquid hydrogen, liquid methane, methanol, ethanol, biodiesel (FAME) and the eighth is Jet A-1, which currently is the standard jet fuel. The energy content (LHV) and energy density are given for each fuel (GREET, 2008) and plotted into a graph in Figure 13. Jet fuel must have a high energy content and high energy density to keep weight and volume of the aircraft down. The energy content (y-axis) is given in kg/100MJ and the energy density (x-axis) is given in liters/100MJ. Fuels that have similar characteristics could be used as drop-in replacement. Aircraft need to be redesigned probably for fuels that do not fall in this area. It is likely to conclude that biofuel should have a similar energy and volumetric density as Jet A. Redesigning of aircraft is avoided in that way and the biofuel can be used as drop-in replacement.

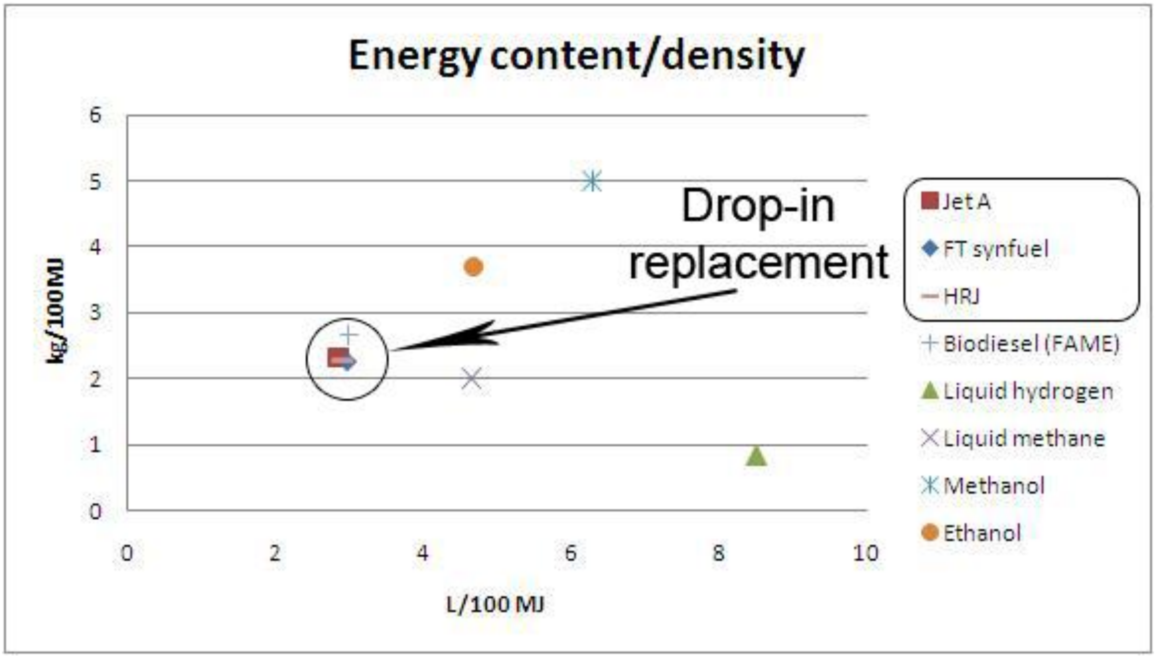

Figure 13 Energy content/energy density several fuel types (Greet, 2008). Fuels that have similar energy content/density could be used as drop-in replacement.

Fatty acid methyl ester (FAME) is made from pure plant oil (PPO). It scores high for energy content/ density, but it is less suitable for aviation. A real issue is the high freezing point which is roughly +4ºC. Another issue is the bio-degradability of FAME which is affecting stability of the fuel (Clark, 2008). FT synthetic fuel is a suitable jet fuel and has been certified for a blend up to 50% of FT synthetic fuel and petroleum-derived jet fuel (ATI, 05/08/09). ASTM is expected to certify blends up to 50% HRJ and petroleum-derived jet fuel in 2010 (Flight International, 12/10/09). This means both alternative fuels are suitable to propel aircraft.

4.2 Production of macro algae

Macro algae cultivation is done for almost a century. The production of macro algae takes place in four essential steps. These are seeding, fertilizing (optional), harvesting and transport, see Figure 14 and each of these processes are discussed.

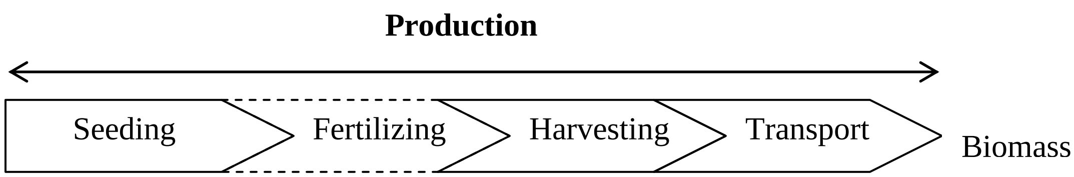

Figure 14 Processes in biomass production.

Firstly, some historical background is given about macro algae cultivation. Macro algae are cultivated for several purposes. Secondly, the macro algae cultivation method is discussed. The location and nutrient availability do affect the productivity of macro algae and will be discussed as well. Finally, the harvesting method and transport are mentioned and this completes the production process.

4.2.1 History

Macro algae are cultivated commercially for almost a century. Macro algae farming started in California before the First World War. Potassium was used to produce gunpowder and Germany was the largest supplier at that time. The supplies were stopped when the war started and other potassium sources were needed. Macro algae contain potassium and macro algae were cultivated on a large scale at the coast of California. Production declined after the First World War. Later on, macro algae were produced as algin source, an ingredient for the food industry. Monitoring worldwide macro algae production by the Fisheries and Agricultural Organisation from the United Nations (FAO) started in 1950. Production grows annually, see Figure 15 for global macro algae production. Asia is almost fully responsible for the total global production. Macro algae quantities which are produced in America, Africa, Europe and Oceania are negligible.

FAO is monitoring annually the revenues from macro algae since 1984. The quantities in wet ton and price in $2009/ton are shown in Figure 16. The quantities are growing exponentially in the period 1984-2007. An exponential trend line in the price is added as well. The trend lines are further used in section 5.2 to determine the price of bio jet fuel.

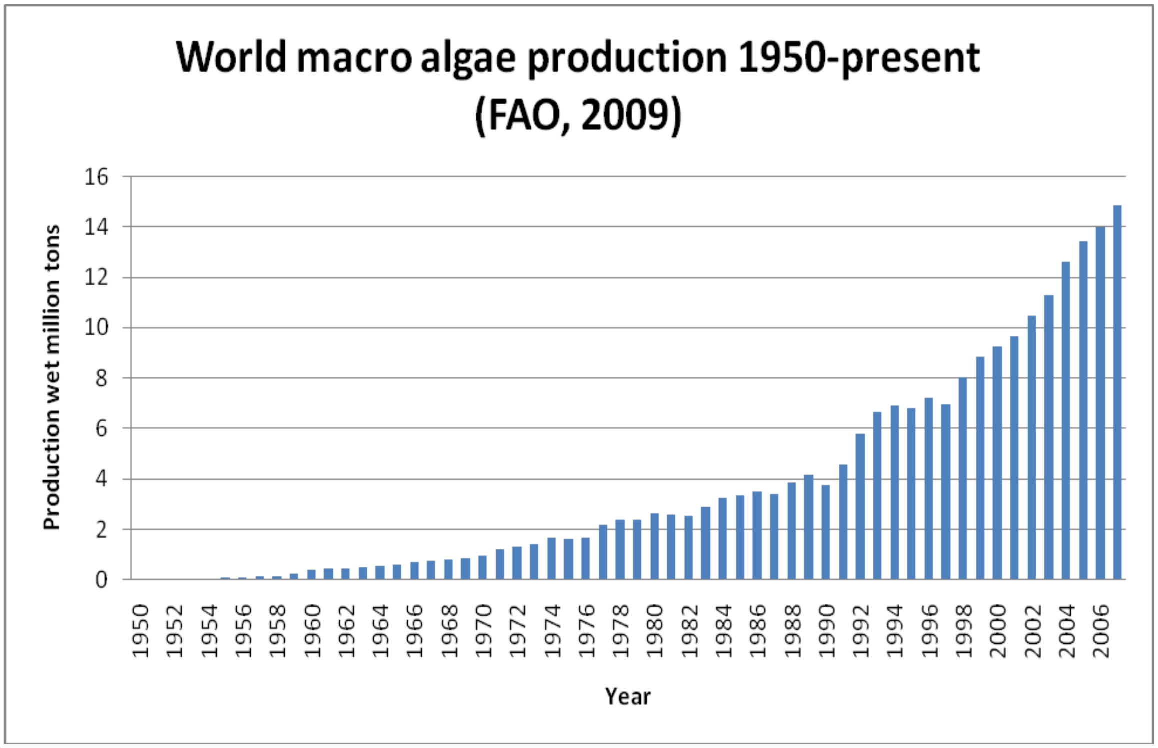

Figure 15 World macro algae production 1950-2007 (FAO, 2009). Asia is almost fully responsible for macro algae production.

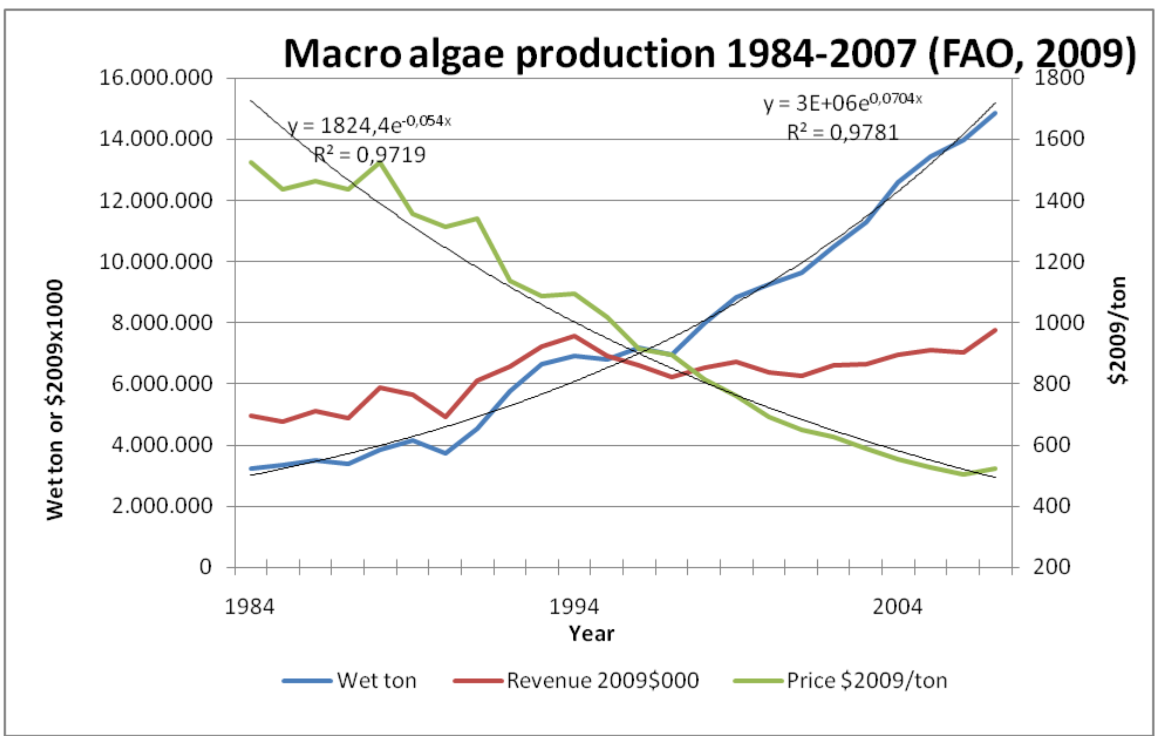

Figure 16 World macro algae production quantities and price evolution 1984-2007 (FAO, 2009). The blue line represents the wet macro algae production. The green line represents the macro algae price in $2009/ton. A regression line is plotted and both are a good fit, R^2 =0.97.

4.2.2 Cultivation method

In the world thousands of algae species exists, all having their own characteristics in growth ratio, some of them are floating or some of them are attached etc. Algae need three elements to grow which are light, carbon and nutrients. Bird (1987) described four cultivation methods and made a distinction in yields between baseline and advanced cultivation. Baseline is macro algae yield in the start-up phase. Advanced is a method when yields improve. Yields are given in dry ash free metric tons (DAFMT). The main components are carbon, hydrogen and oxygen. Values are given in US1987$.

Near shore Macrocystis

Kelp species Macrocystis is planted near shore in water depths of 8-18 metres. Small plants are fastened to bags of rock aggregate, see Figure 17. These are lowered to the bottom with lines which also space the plants apart from each other. The Macrocystis forms a kelp forest and is harvestable after two years. From the baseline analysis was assumed, a kelp yield of 34 DAFMT/ha/yr and for an advanced analysis 50 DAFMT/ha/yr. Experiments showed these yields were not sustainable without replant, but new planting configurations would improve yields. The feedstock costs for the baseline and advanced method are 67 $/DAFMT and 42 $/DAFMT, respectively.

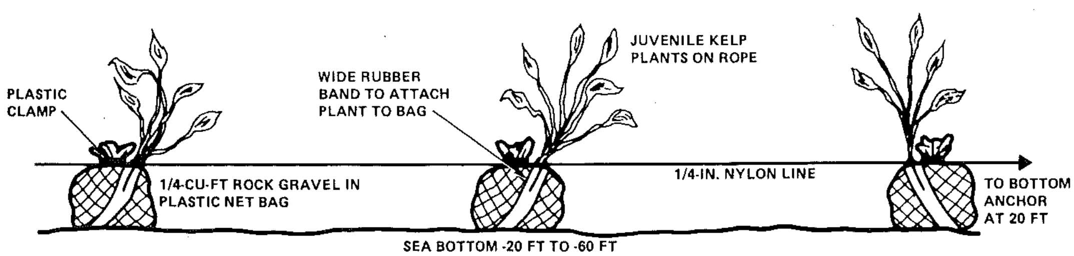

Figure 17 Nearshore macro algae farming. Macro algae are planted on the bottom of the sea. They form a kelp forest and can be harvested (Bird, 1987).

Laminaria-Gracilaria Multicrop system

This cultivation concept was designed for a cultivation system at the coast of New York. Laminaria would be grown in the winter months and Gracilaria during the summer months. These macro algae grow on a rope in water depths averaging 80 metres, see Figure 18. The Japanese developed a Laminaria cultivation system on ropes and achieve yields of 7-16 DAFMT/ha/yr. New goals were set to 45 DAFMT/ha/yr. In this experiment, baseline yields were assumed to be 11 DAFMT/ha/yr and advanced 45 DAFMT/ha/yr. The rope systems turned out to be expensive. High capital and maintenance costs were necessary. The feedstock costs would be 538 $/DAFMT and 147 $/DAFMT, respectively, for the baseline and advanced analysis.

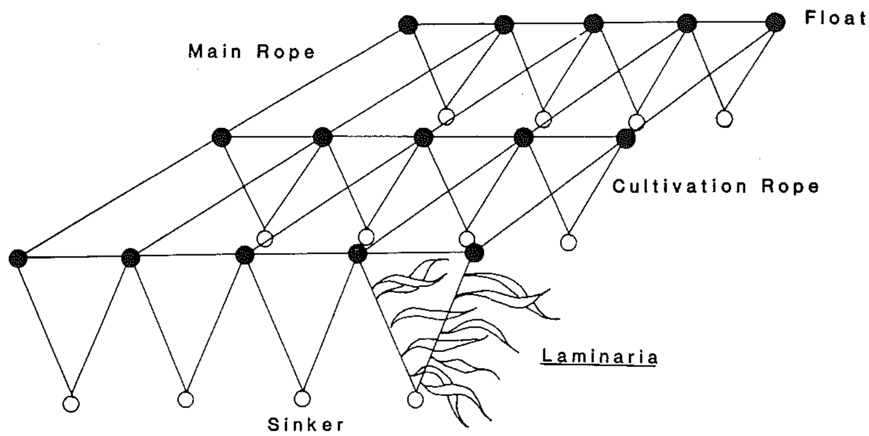

Figure 18 Rope macro algae farming. Macro algae are attached to ropes. The ropes are taken onboard a ship and algae can be harvested (Bird, 1987).

Tidal flat farm

In a tidal flat farm, the kelp species Gracilaria or Ulva are cultivated in coastal waters with depths of 0.5-1.5 metres, see Figure 19. Nets supported by pilings surround the cultivation area. The macro algae grow in the enclosure and are harvested by small boats. Yields in commercial Gracilaria pond cultivation in Taiwan are 8 DAFMT/ha/yr. In this concept yields in the baseline and advanced concept are estimated to be 11 and 23 DAFMT/ha/yr and feedstock costs are 44 $/DAFMT and 28 $/DAFMT, respectively.

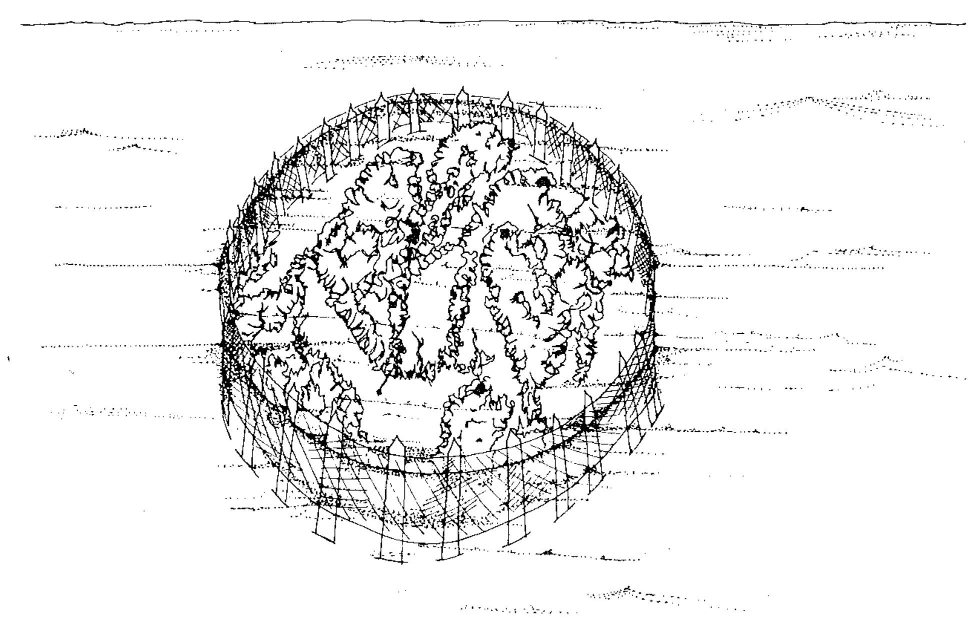

Figure 19 Tidal flat macro algae farming. Tidal shores are planted with macro algae. A fence or other containment system keeps the macro algae within the designated area (Bird, 1987).

Floating macro algae cultivation

Some macro algae species such as Sargassum have free-floating capabilities. Large expenses could be saved when these floating macro algae are cultivated. Ropes or other attachments are not necessary anymore, only a containment system, see Figure 20. Capital costs for a containment system are combined with harvesting costs for near shore cultivation. The yields were assumed to be 22 and 45 DAFMT/ha/yr with feedstock costs of 73 $/DAFMT and 37 $/DAFMT.

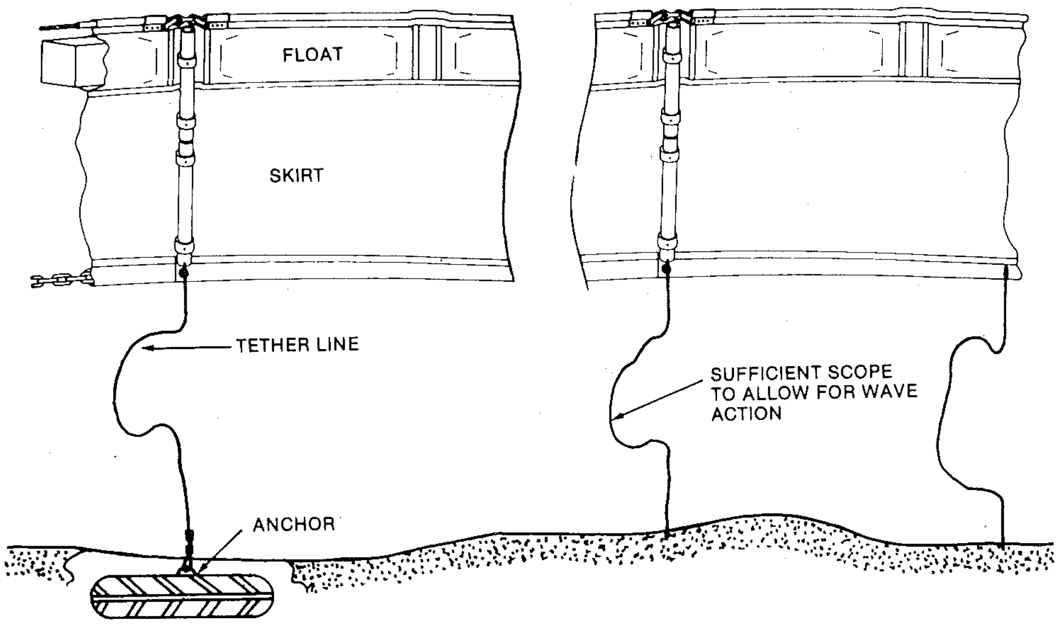

Figure 20 Floating macro algae farming. Some macro algae have free-floating capabilities. These can be cultivated in oceans. A containment system keeps them on the designed area (Bird, 1987).

All data about yields and feedstock costs are summarized in Table 1. This data is further used for the trade-off.

Table 1 Feedstock costs cultivation methods (Bird, 1987). This contains a yield and cost estimation of the four cultivation methods. Rope farms are substantially more expensive. Near shore, tidal flat farms and floating macro algae have cultivation costs in the same range.

System	Analysis	Yield DAFMT/ha/yr	Feedstock 1987$/DAFMT
Near shore Macrocystis	Baseline Advanced	34 50	67 42
Rope Farm Gracilaria, Laminaria	Baseline Advanced	11 45	538 147
Tidal Flat Farm Gracilaria, Ulva	Baseline Advanced	11 23	44 28
Floating macro algae Sargassum	Baseline Advanced	22 45	73 37

Trade-off cultivation system

Four cultivation systems described above are compared to several criteria. The selection criteria are:

- Capacity: yields are compared for efficient cultivation.
- Sizing: The area needed to cultivate macro algae to fulfil jet fuel demand.
- Economics: the cost price should be economically competitive with global market fuel prices in the long term.

The four cultivation systems are compared in Table 2. Kelp farming on ropes is more expensive than the other three systems. Large coastal areas in Europe are extensively used for leisure purposes. Besides that, coasts are areas with special ecological values, see Figure 27. Tidal flat farms do not seem to be an ideal cultivation method. On the other hand, feedstock costs are the lowest of all, but the difference between near shore and floating is not significant. That leaves two suitable cultivation systems: near shore and floating macro algae. Guiry (1991) stated that "no complex mechanical structure has been economically successful in growing attached macro algae". The cultivation should be simple.

Table 2 Comparison cultivation systems. Four cultivation systems are analysed to three criteria. Near shore and floating macro algae farming appear to be most suitable.

	Capacity	Sizing	Economics
Nearshore macro algae farming	+	+	+
Rope macro algae farming	-	+	--
Tidal flat macro algae farming	-	+-	+
Floating macro algae farming	+	+	+

Alga species

There are thousands of alga species in the world. Only a couple of them are mentioned to use in cultivation systems. With the exclusion of rope farms and tidal flat farms, two algal species are left: Macrocystis and floating Sargassum. Both belong to the brown algae. It is assumed that these two are the best species (Bird 1987, Herfts 2008), but other suitable species could appear in the future. The brown algae, as the name suggests, has a brown colour and are common in cold waters along continental coasts. They multiply by sexual or asexual reproduction. Sargassum *natans* and *muticum* occur in the North Sea, Guiry (1991). Some species grow in shallow water and coral reefs and some have a free-floating capability. The two species Sargassum *natans* and Sargassum *fluitans* float on the sea surface their entire life. These algae have been named after the Sargasso Sea, which hosts large amounts of Sargassum algae. Sargassum is one of the few macro algae species that has the capability to fix nitrogen from the atmosphere. Phosphorus appears to be the limiting factor in growth (Bird, 1987). Nutrients are further discussed later on in this section.

Macrocystis is a kelp species which can grow up to 60 meters. The kelp grows on the sea floor or other hold on. Macrocystis *pyrifera* is also known as the giant kelp and belongs to the fastest growing organisms in linear direction. This alga grows at the coastal lines from Alaska to California, South America, South Africa, Southern Australia and New Zealand. Once Macrocystis are seeded or planted and settled, the algae are harvested by cutting and lifting them out of the water.

The chemical composition of Sargassum and Macrocystis are required to calculate conversion into jet fuel. No data about Macrocystis and Sargassum were found. It is assumed that Laminaria, which belongs to the brown algae, has similar chemical composition. Table 3 shows the chemical composition of Laminaria and all data about Laminaria can be found in Appendix 2. The composition is visualized in Figure 21 from which the carbon and hydrogen atoms are required for biofuel. It is clear from the analysis that only a small fraction of wet alga is used to produce biofuel.

Table 3 Chemical composition of species Laminaria (Reith, 2005).

	Laminaria
Dry matter	12% of wet weight
Ash content	26% of dry weight
DAF	74% of dry weight
Carbon	34.6% of dry weight
Hydrogen	4.7% of dry weight
Oxygen	31.2% of dry weight
Nitrogen	2.3% of dry weight
Sulphur	1.0% of dry weight
Phosphorus	0.4% of dry weight
LHV	12.2[1] MJ/kg dry weight
HHV	13.2 MJ/kg dry weight
LHV	16.5 MJ/kg DAF

[1] Calculated from HHV

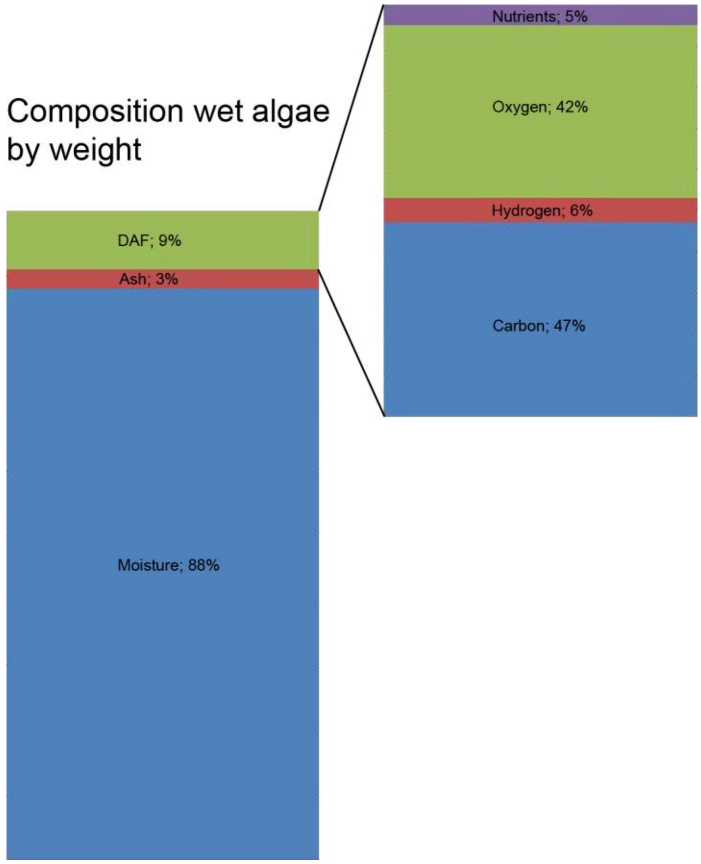

Figure 21 Composition wet alga by weight. The carbon and hydrogen atoms are required for bio jet fuel production. This is a small fraction of the wet algae.

Research into alga species

It is possible that more species are suitable. That is why more research into algae is necessary. The focus has to be on these requirements:

- Production
    - Ease of seeding
    - Ease of harvesting
    - Fertilization
    - Yields per hectare per year
    - Resistant to diseases
    - Feedstock costs
- Conversion
    - Ease of extraction
    - Conversion efficiency
    - Cake or ash suitable for sale
    - Conversion costs

4.2.3 Nutrients

This section is dedicated to nutrient needs for biomass. Biomass absorbs nutrients to grow and it is one of the three essential elements. These nutrients are released again when biomass degrades. The nutrients become available again as fertilizer, or flow into the water system. Available nutrients in natural conditions are limited. Fertilizers are produced to increase crop yields in agriculture. The nutrient flows are analysed in this section with the aim to make it a renewable production.

Current situation

Fertilizers are used on a large scale in modern agriculture to increase yields per hectare. Since the day fertilizers were introduced, yields per hectare increased simultaneously. The Fisheries and Agricultural Organisation (FAO) monitored the area used for global wheat production, wheat yields per hectare and the total consumed fertilizers globally, see Figure 22. In this graph, a steady area is visible while the yields and fertilizer consumption rise simultaneously. It can be concluded fertilizers play a major role in food production.

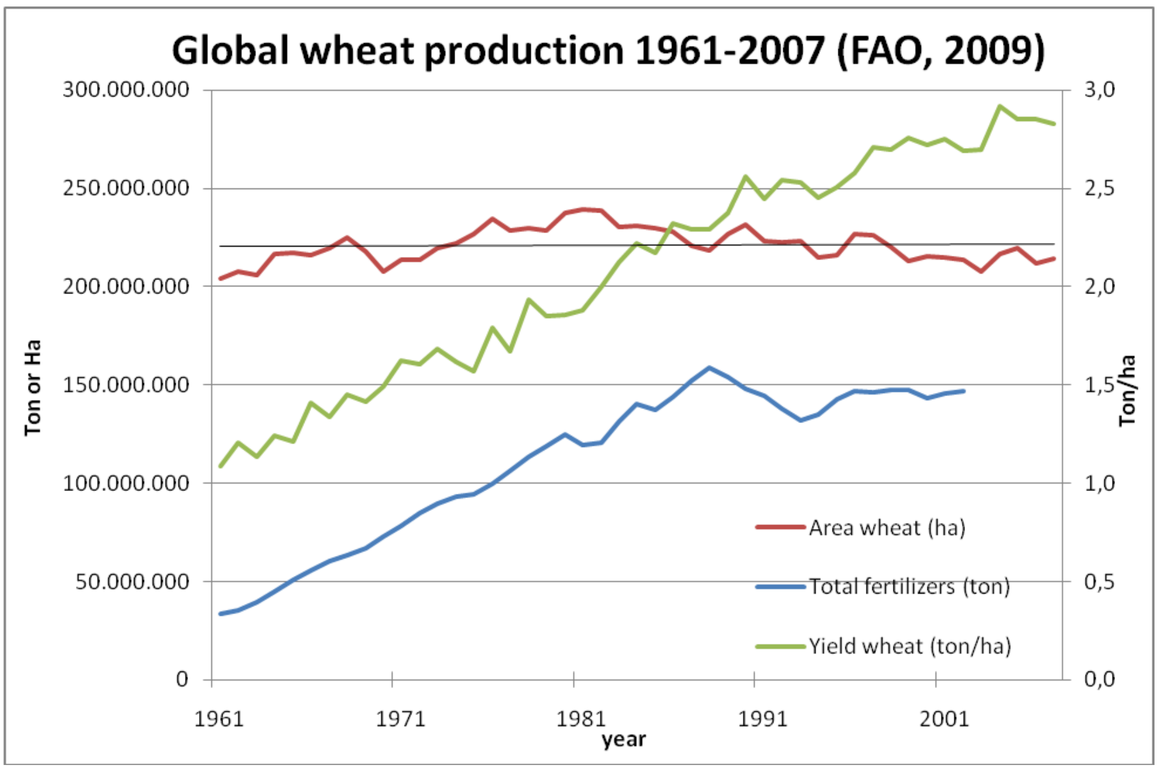

Figure 22 Global wheat production and fertilizer use (FAO, 2009). The yield in ton/ha is rising thanks to the introduction of fertilizers.

Main elements in fertilizers are nitrogen (N), phosphorus (P), potassium (K) and micro-elements magnesium (Mg), iron (Fe), copper (Cu), manganese (Mn), zinc (Zn) and molybdenum (Mo). Nitrogen and phosphorus are needed in the largest quantities in biomass. These two are discussed further.

Nitrogen
78% of the earth's atmosphere volume consists of nitrogen. Although the large appearance on earth, biomass is not able to absorb nitrogen in this form. Nitrogen fertilizer is mainly produced with the Haber-Bosch process which produces Ammonia (NH_3). The reaction which occurs is:

$N_2(g) + 3H_2(g) \rightarrow 2\ NH_3\ (g)$.

Hydrogen is required for this reaction and it is mainly produced from methane gas with the natural gas steam reforming process. In the first reaction called steam reforming, methane is converted with water into carbon monoxide and hydrogen.

$CH_4 + H_2O \rightarrow CO + 3\ H_{2.}$

In the second reaction, carbon monoxide is converted with water into carbon dioxide and hydrogen, which are the two reactants of the total process.

$CO + H_2O \rightarrow CO_2 + H_{2.}$

Hydrogen production is an energy consuming process and the hydrogen energy efficiency is 89.3%. Carbon dioxide emissions are 11.9 kg CO_2/kg Hydrogen, (Spath, 2001). The average energy consumption and carbon dioxide emission for nitrogen production are 40.3 MJ/kg N and 5.29 kg CO_2/kg N (Kongshaug, 1998).

Phosphorus
Phosphorus fertilizer is commonly used in the form H_3PO_4. Phosphorus is recovered in inorganic phosphorus rocks. China, Morocco and Western Sahara contain about two third of the global phosphate reserves, see Table 15 and Figure 54 in Appendix 4. Global reserves are divided into reserve: economically recoverable proven phosphate rocks and reserve base: not economically recoverable proven phosphate rocks. Phosphate rocks reserves are depleted after 90 years if demand remains steady (Jasinski, 2009). The average energy consumption and carbon dioxide emission for phosphorus production are 3.4 MJ/kg P and 0.22 kg CO_2/kg P (Kongshaug, 1998).

Phosphorus uptake in Chinese agriculture is 45% and in the UK about 55% (Chen, 2008). That means about half of the supplied phosphate fertilizers directly flow into the fresh water system and oceans. Fertilizers which are absorbed by plants ultimately end in fresh water system and oceans, see Figure 23 for the total phosphate flow. Phosphate rocks are mined more quickly than they are formed by the ocean sediments. It will become scarce if mining continues in the same conditions. The aim is to extract nutrients from wastes and wastewater streams to recycle them.

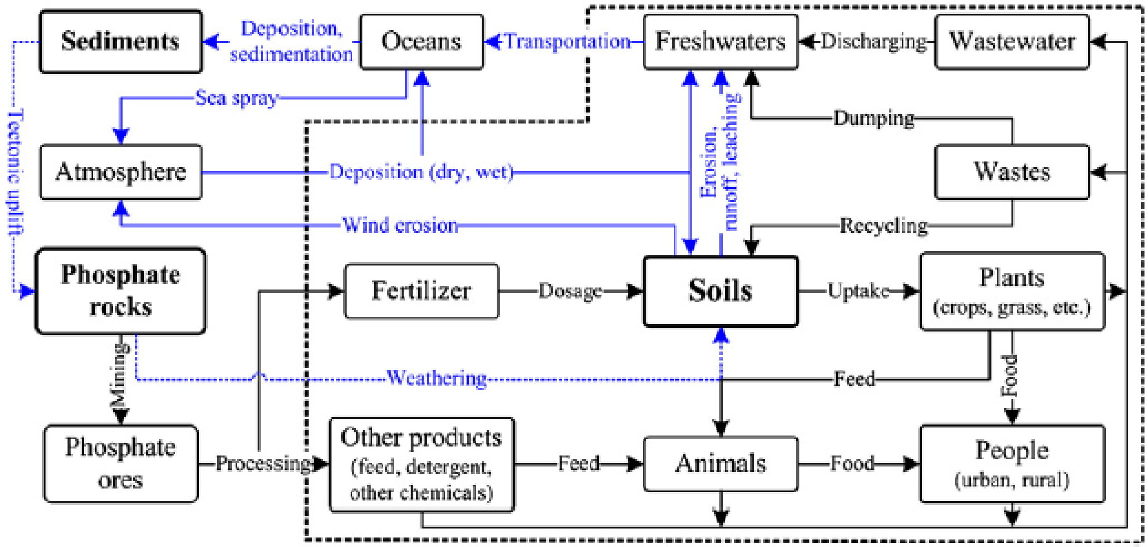

Figure 23 Phosphate flows (Chen, 2008).

Nutrient requirements macro algae

In Table 3 the chemical composition of the macro algae species Laminaria is given (Reith, 2005). Carbon, hydrogen and oxygen appear in the form of carbon dioxide and water. Nitrogen and phosphorus appear to be the limiting factor in macro algae growth, Bird (1987). Gao (1994) states that macro algae are formed with this reaction:

$$550CO_2 + 580H_2O + 30HNO_3 + H_3PO_4 \rightarrow (CH_2O)_{550}(NH_3)_{30}H_3PO_4 + 610O_2 \quad \text{(Gao, 1994)}$$

From this formula, the C:N:P ratio (weight) is 213:14:1. From the chemical composition analysis in Table 3, a ratio of 87:6:1 is found. C:N ratio is equal and the N:P ratio is about half. Ratio 87:6:1 from Table 3 is further used for nutrient calculations. A major innovation in Chinese intensive near-shore kelp cultivation was the introduction of fertilizer. The Chinese applied fertilizer by putting them in the clay. Later on, they sprayed them with a helicopter or from boats. Fertilizers are effective in intensive cultivation areas in calm water, Bird (1987). Additional research is necessary to see whether additional costs will return in increased kelp yields.

Large quantities of nitrogen and phosphate are required for cultivation. A demand of 3.7 million tons jet fuel per annum in the Netherlands is assumed. With a yield of 0.29 ton fuel/DAFMT macro algae, 0.109 ton Nitrogen/ton fuel and 0.019 ton Phosphate/ton fuel is required. This means the total demand of nitrogen and phosphate is 400 thousand tons and 70 thousand tons, respectively. This is larger than the fertilizer use in Dutch agriculture in 2007, which was 258 thousand tons and 16 thousand tons for nitrogen and phosphate (CBS, 2009). However, fertilizers cost money and the production is energy consuming. Fertilization can be reduced when algae are cultivated in nutrient-rich waters. Tests must confirm the productivity of algae in these nutrient-rich waters. Residues from algae that were used to produce fuel can be used for fertilizer as well. This has been done before and seems to be promising, Gao (1994). Florentinus (2008) researched the possibility to cultivate algae in nutrient rich waters. Coastal waters or deltas are usually nutrient rich. Nutrients from sediments and fertilizers from farmland flow into rivers and coastal areas. Chlorophyll is an element in biomass and is necessary for photosynthesis. Higher concentration chlorophyll means more biomass because of more nutrients. Figure 24 shows the chlorophyll concentration in waters. Florentinus (2008) reports the coastal areas that are marked white do not need fertilization. Totally, an estimated 3.7 million km^2 nutrient-rich waters are available from which the North Sea.

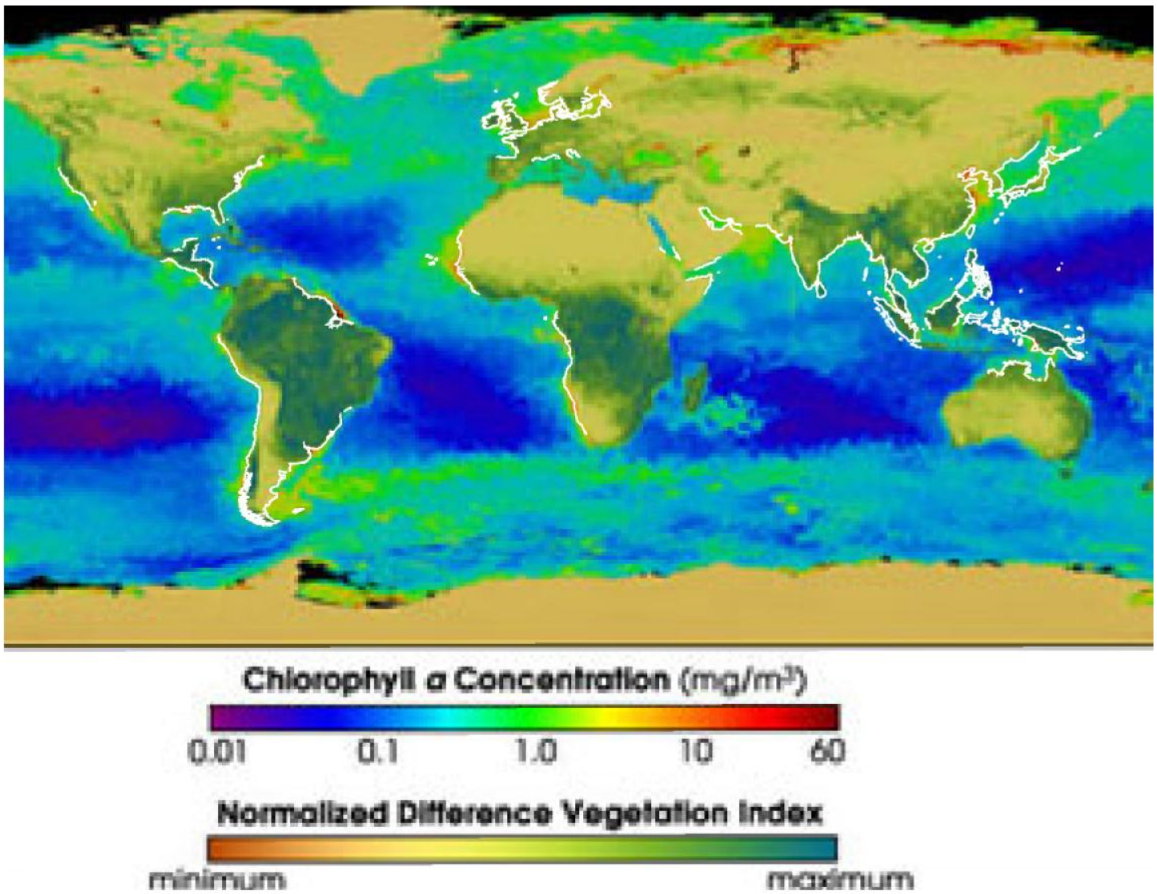

Figure 24 Chlorophyll concentrations, Florentinus (2008).

Hydes (1999) researched nitrogen concentrations and flow in the North Sea. The North Sea is divided into four sections, see Figure 25. Hydes (1999) simulated the available annual nitrogen supply, see Table 4. The highest available concentration of nitrogen was in section four and five. This seems to be logical, because the Rhine delta is at section four and the Elbe delta is in region five. It is obvious to start macro algae farming in region four and five, because of higher nitrogen concentrations.

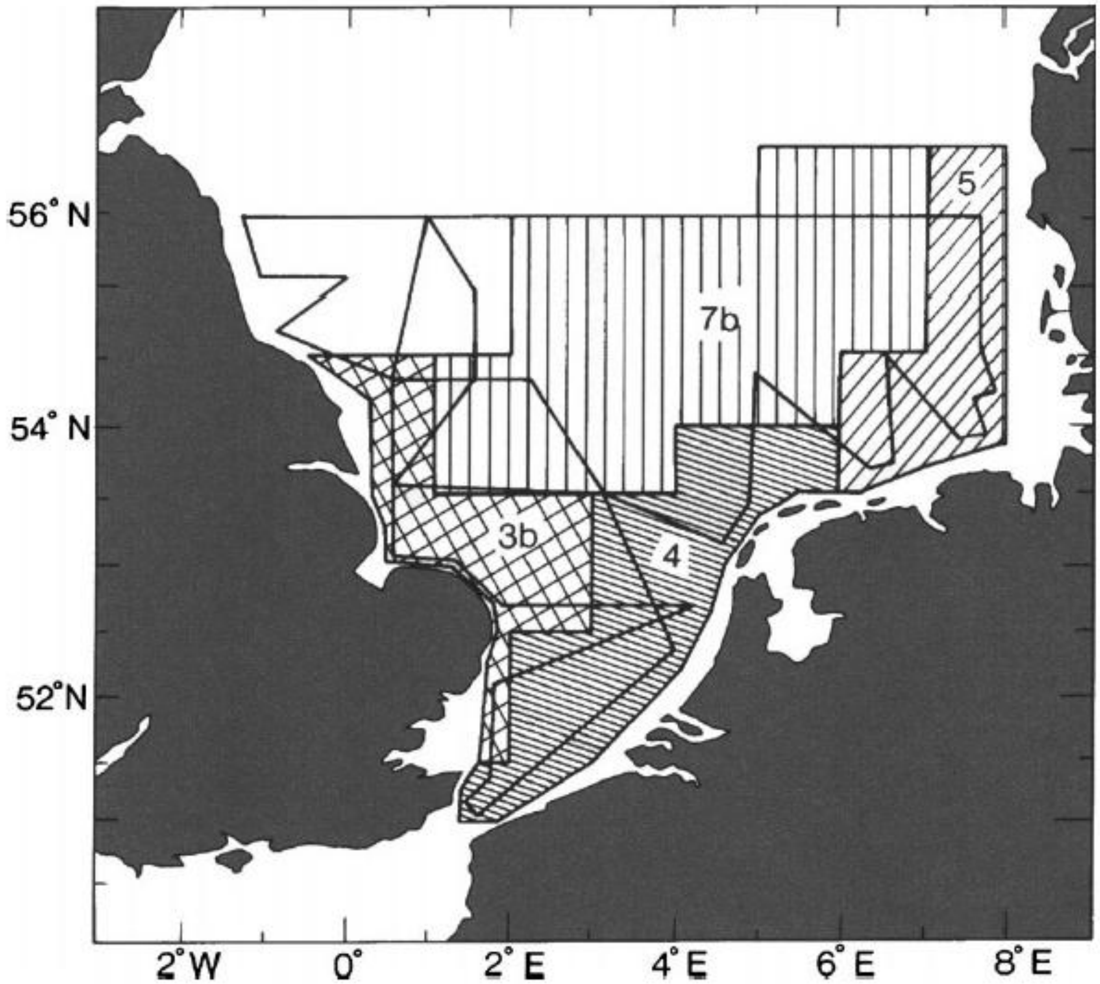

Figure 25 Division North Sea to project nitrogen and phosphorus (Hydes, 1999).

Table 4 Nitrogen concentration North Sea (Hydes, 1999).

Area	kton N	volume km^3	area km^2	ton/km^3	mg/l
3b	168	911	32,544	184.5	0.18
4	265	1,196	44,208	221.6	0.22
5	326	782	36,576	417.1	0.42
7b	398	3,086	77,616	129.0	0.13

Chlorophyll concentrations in oceans are low compared to coastal and river delta areas. This could mean poor nutrient levels. Herfst (2008) and Bird (1987) described in their research into macro algae farming that higher nutrient concentrations in oceans appear at the sea bottom. Nutrients can be transported to ocean surface levels and absorbed by the algae. Bird (1987) started an experiment, but that did not succeed because severe weather destroyed the pilot plant. New experiments were not started because research into macro algae was abandoned. Herfst (2008) made a conceptual design for algae farming with the same principles, see Figure 26.

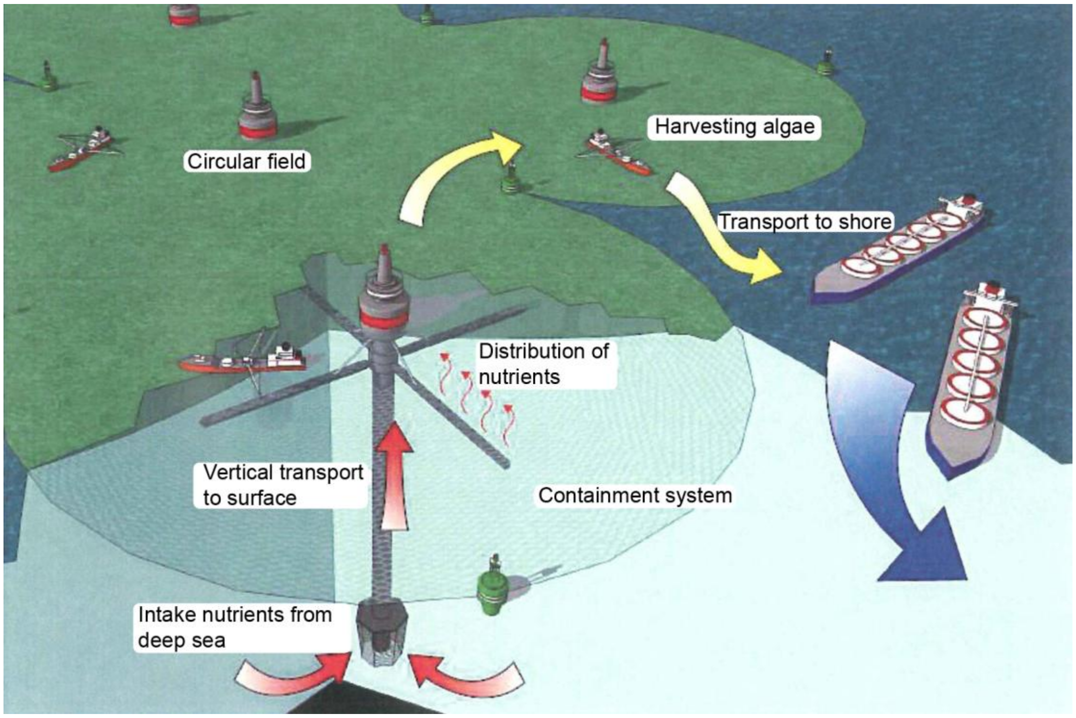

Figure 26 Conceptual design algae farming with nutrients from sea bottom (Herfst, 2008). The sea bottom contains a higher concentration nutrient which is transported to the surface. Macro algae absorb these nutrients and fertilization is avoided.

Recycling nutrients

Fertilizer production is not sustainable in the long term. Nitrogen fertilizers are produced with natural gas resources, and phosphate rocks are limited. In order to solve these issues and fulfil the sustainability aspect, nutrients should be extracted during conversion from macro algae into fuel and recycled to fertilizers again. Nutrient extraction is not analysed further in this research. Two possible options are:

- Option 1: Extract nutrients from the algae and use them immediately as fertilizer for algae cultivation.
- Option 2: Produce fertilizer from extracted nutrients from the algae and use them for agricultural purposes. Nutrients flow to seas in the end where algae can absorb them.

4.2.4 Location

A salt-water area is required where macro algae can be cultivated. Nutrient-rich waters are preferable, as discussed in the previous section. Besides nutrients, carbon and light are essential elements for macro algae. Thousand macro algae species exits worldwide each having own characteristics. Any cultivation location is suitable if the alga species tolerates the local circumstances. The Netherlands has one large salt-water area that belongs to the Dutch waters, namely, the North Sea. Interestingly, the North Sea belongs to the nutrient rich waters (Ecofys, 2008). It is an area with the size of 52.000 km^2 and currently used for shipping routes, sand winning, ecological areas, military purposes, etc. Wind farm areas have been designated in recent years. The aim is to build wind turbines with a total power of 6.000 MW on an area of about 1.000 km^2 by 2020. See Figure 27 for an overview of the Dutch North Sea. Large areas in the North Sea are unused and it is possible to cultivate macro algae in these areas between the wind farms. These areas are all at least twelve miles from shore with depths from 20-80 metres. Transport distances should be short between cultivation, conversion and demand. Mainly, demand for aviation fuel in The Netherlands comes from airlines at Schiphol Airport. It is possible to locate conversion facilities at current refineries in the harbour of Rotterdam. In an ideal situation, all macro algae for bio jet fuels for Dutch demand are cultivated in the North Sea.

As said before, nutrients are the limiting factor in macro algae growth (Gao 2007, Bird 1987). If fertilizers are applied, light might become the limiting factor. The average solar irradiance in the last decade at the North Sea is 3.5 $GJ/m^2/year$ (110 W/m^2). See Appendix 5 for the annual mean solar radiation on earth. Equatorial waters have more solar irradiance. If light becomes the limiting factor, it is possible to move cultivation to more light intensive areas to increase yields.

Sizing

This section will discuss how much area is needed for macro algae cultivation to produce the demanded jet fuel in the Netherlands. Demand was 3.7 million tons of aviation fuel in 2008 (CBS, 2010). The algal biomass is supposed to grow on the Dutch North Sea. The area needed depends on how much algal biomass is produced per hectare. In the previous section, the yields are ranging from 22 to 50 DAFMT/ha/yr. These yields were not sustainable during the experiment, but these could become sustainable when experience with cultivation is gained (Bird, 1987). Yields in this research are conservative, ranging from 12 to 30 DAFMT/ha/yr. 12 DAFMT/ha/yr (baseline) seems to be sustainable in the short term, because yields in California are obtained of 12.3-14.8 DAFMT/ha/yr for fertilized beds, Doty (1987). With these yields, fuel production is 3.4-8.6 net ton fuel/ha/yr, respectively. This is more productive compare to yields of other feedstocks: Jatropha 1.5 ton/ha/yr, Palm oil 4.8 ton/ha/yr and Camelina 1 ton/ha/yr (Chisti, 2007). The area required for macro algae cultivation is 10,807-4,323 km^2, respectively. All relevant numbers are summarized in Table 5.

Table 5 Sizing Dutch aviation fuel demand.

Sizing			
Aviation fuel	3,70E+06	ton/yr	
Dutch North Sea	52000	km^2	
Yield	12	30	DAFMT/ha/yr
Net fuel yield	3,4	8,6	Net ton/ha/yr
Area	10.807	4.323	km^2
Percentage of Dutch North Sea	20,8%	8,3%	

The Dutch North Sea has an area of 52.000 km^2. When algae yields are 12 DAFMT/ha/yr, more than twenty percent of the Dutch North Sea is needed for macro algae cultivation, which is substantial. This becomes less when yields and productivity increase. See Figure 27 for sizing macro algae cultivation in the North Sea. On a global level to fulfil the worldwide aviation fuel demand, an area of 71 million hectares is required for a yield of 12 DAFMT/ha/yr, which is the size of Turkey.

Another constraint in location is the sustainability aspect. The macro algae cultivation should happen in areas that does deplete or destroy natural resources. For example, cultivation should not be done in waters with highly ecological values such as coral reefs, fish breeding areas etc. The location should be judged on these criteria before cultivation can start.

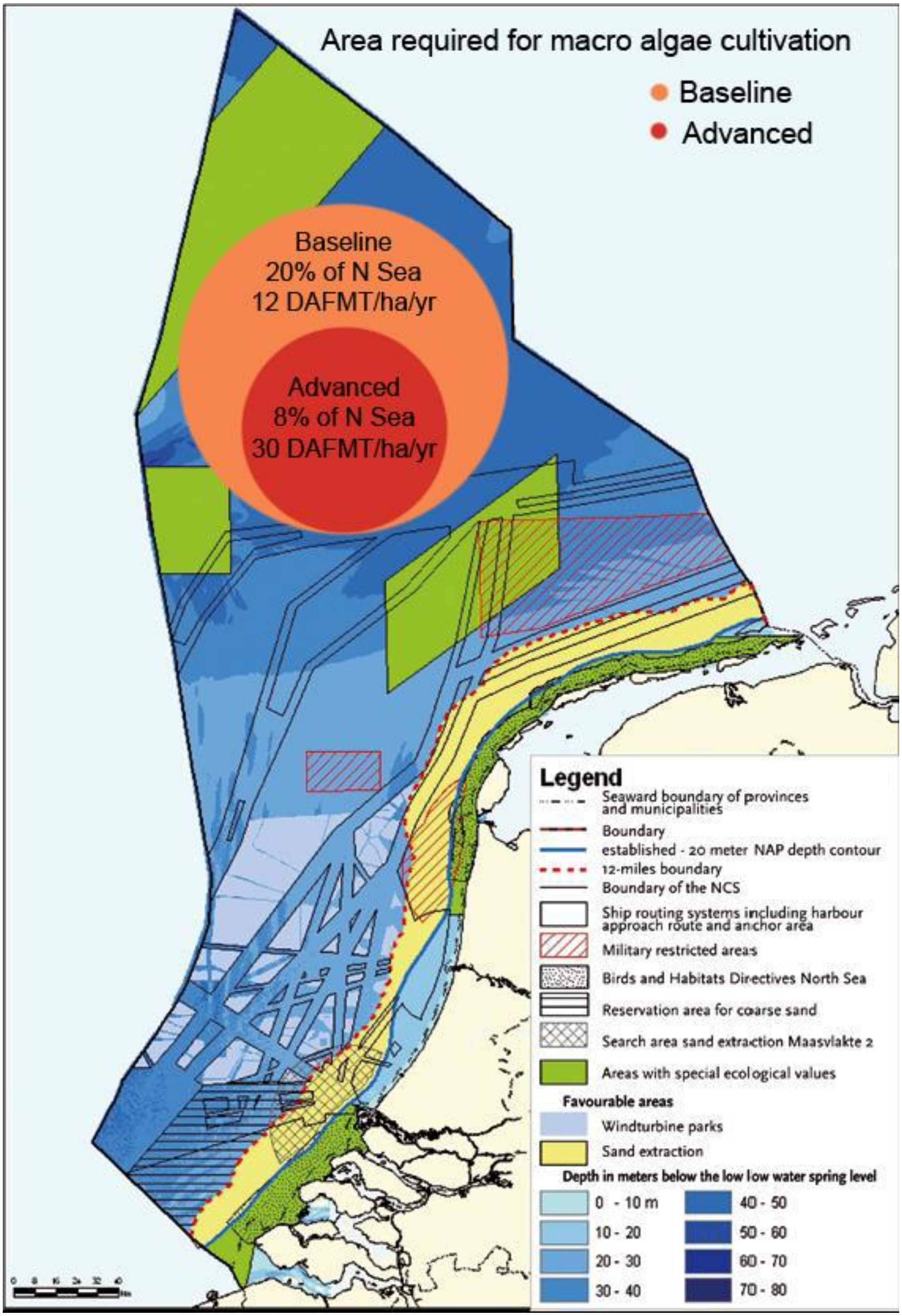

Figure 27 Dutch North Sea (Dutch ministry of transport, public works and water management, 2005).

4.2.5 Harvesting

Harvesting macro algae can be done in two ways. Firstly, macro algae can be harvested by hand, which is common in South East Asia. Secondly, macro algae can be harvested by machinery, which is preferable for large quantities. Harvesting ships (see Figure 28) have been developed and are operational for kelp farming on the west coast of the USA. These ships are capable of harvesting floating and attached macro algae. The attached macro algae are cut and brought onboard. The floating macro algae are brought onboard without any further handling. The macro algae are stored onboard and transported in barges that bring them to shore, where they are converted into biofuel. The largest transport distance from the North Sea to the port of Rotterdam is about 200 kilometres.

Figure 28 Macro algae harvester.

All relevant specifications of the harvester are given in Appendix 6, Table 16. In these calculations, it is assumed that the harvester is operational 300 days per year. 65 days per year are reserved for bad weather conditions. A harvester harvests 67 hectares per day with a daily production of 800 DAFMT.

Transport from production to conversion

The wet algal biomass which is harvested is poured into barges. The barges have a capacity of 2000 ton each and are pushed by one tug to the conversion facility. The fuel consumption is determined from the average fuel consumption of a ship. To move one ton over one kilometre 0.0045 kg fuel is consumed, Chiffi (2009). 0.10 kilogram carbon dioxide is emitted per kilogram fuel and the energy used is 0.028 MJ/MJ_{fuel}. All relevant data are given in Appendix 6.

4.3 Conversion algae into bio jet fuel

The next major step in bio jet fuel production is the conversion from wet algal biomass into bio jet fuel. Several conversion routes have been developed, which were discussed in section 4.1. Two types fuel are suitable as bio jet fuel which are FT synfuel and HRJ. The conversion routes are further discussed in this section. In short, the conversion consists of two processes, namely, the extraction process and upgrading process, see Figure 29. The final process of the end-to-end chain, delivery to the airline, is included as well.

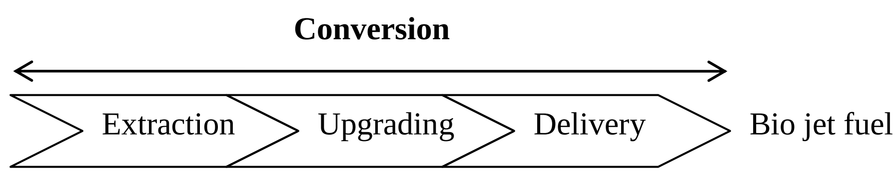

Figure 29 Processes in conversion.

A trade-off is performed between the extraction methods, the extraction and upgrading processes are explained further.

4.3.1 Trade-off conversion biomass to liquids

There are several thermal conversion processes to convert biomass into liquid fuels. As already said before, macro algae is a lignocellulosic biomass and can be converted via three routes into bio jet fuel namely: gasification with Fischer-Tropsch (FT synfuel), pyrolysis with upgrading (HRJ) and hydrothermal liquefaction with upgrading (HRJ), see also Figure 30. Each of these processes is described briefly and the trade-off is performed afterwards.

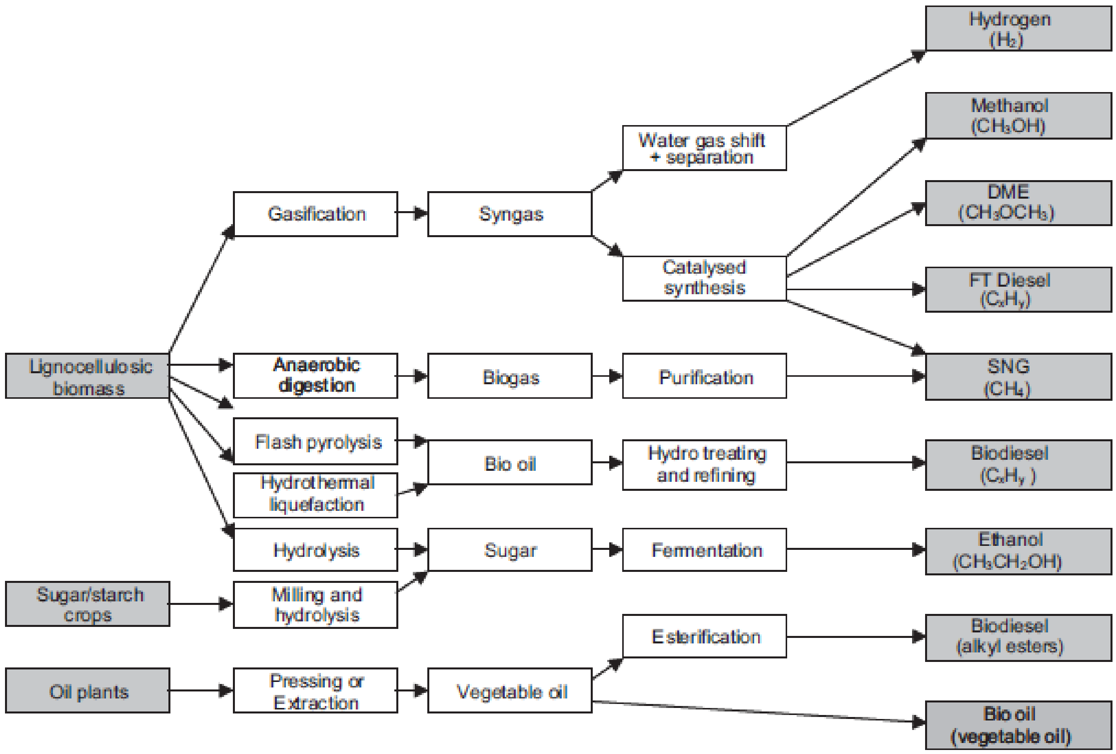

Figure 30 Conversion routes from biomass to liquid fuels (Hamelinck, 2006). Three suitable routes to bio jet fuel are with Fischer Tropsch, pyrolysis or hydrothermal liquefaction.

Gasification with Fischer-Tropsch, Speight (2008)

This process from biomass to liquids takes several steps and the main processes are gasification of biomass into syngas and the conversion of this syngas into liquid fuel by using the Fischer-Tropsch process. The biomass with maximum moisture content of 15 percent goes into a gasifier to produce syngas, a mixture of hydrogen and carbon monoxide. Synthesis gas for use as a fuel is produced by the following paths:

$$C + O_2 \rightarrow CO_2$$
$$CO_2 + C \rightarrow 2CO$$
$$C + H_2O \rightarrow CO + H_2$$

Biomass contains more elements than just carbon atoms. The syngas contains sulphide, alkalis and other contaminants. Some cleaning processes, washing, drying, etc. occur to get a clean mixture of carbon monoxide and hydrogen.

The syngas goes through the Fischer-Tropsch reactor. The conversion to paraffin (FT synfuel) takes place with the help of a metal catalyst. The overall Fischer Tropsch synthesis is described by the general equation:

$$n(CO + 2H_2) \rightarrow (CH_2)_n + nH_2O$$

Pyrolysis with Upgrading, Bridgewater (2000)
Pyrolysis is a process in which the biomass is rapidly heated in the absence of air, vaporises and condenses to a bio-oil which has an heating value of about half of conventional fuel. Essential features of a fast pyrolysis process are:

- Very high heating and heat transfer rates that requires a finely ground biomass feed.
- Carefully controlled temperature of around 500ºC.
- Rapid cooling of the pyrolysis vapours to give the bio-oil product.

The bio-oil which is produced needs a hydrotreatment process to upgrade the pyrolysis oil to aviation standards HRJ.

Hydrothermal liquefaction with upgrading, Goudriaan (2003)
Wet macro algae are treated in a temperature range of 300-350 ºC and a pressure of 12-18 MPa. This process is also called High Thermal Upgrading (HTU). Oxygen molecules are removed in the form of carbon dioxide and water. Biocrude is formed and has a lower heating value (LHV) of 30-35 MJ/kg which is less than required for aviation fuel. The biocrude contains oxygen which amounts 10-20% of the weight. A hydrotreatment process is required to upgrade the biocrude to a high quality fuel (HRJ).

Trade-off discussion
The three possible routes to convert macro algal biomass into biofuel are compared in Table 6 on wet/ dry supply, capacity, economy, CO_2 balance and energy balance. The reasons for these selection criteria are:

- Wet/ dry supply: macro algae are supplied wet and, if drying is necessary, an extra treatment is required. Energy is required for drying, so it is unfavourable for the energy balance.
- Capacity: demand from airlines must be fulfilled and conversion plants must have a capacity to fulfil this demand.
- Economy: conversion plants must be economically competitive with global market fuel prices in the long term.
- Carbon dioxide balance: CO_2 emissions must be in line to reduce the emissions in the end-to-end chain.
- Energy balance: the energy balance in the end-to-end chain must be positive.

The comparison in Table 6 between the three conversion routes has already been performed by Goudriaan (1990). Pyrolysis is a process with unknowns about the economy and carbon dioxide balance. The energy balance is zero, which means the energy produced is equal to the energy supplied for the process. Overall, the process is not suitable as a conversion process. The other two processes (gasification with Fischer-Tropsch and HTU with upgrading) are suitable and comparable in capacity, economy, carbon dioxide balance and energy balance. The only difference is biomass supply. Gasification requires dry supplied biomass, whereas HTU requires wet biomass. With the eye on large cultivation, large capacity and drying, supply of wet biomass is favourable.

As such, HTU with upgrading is chosen as conversion process and further used in this research.

Table 6 Compared conversion routes (Goudriaan, 1990). HTU appears to be the most suitable conversion route from biomass to biofuel. No drying of feedstock is required for this conversion route.

	Wet/ dry supply	Capacity	Economy	CO_2 balance	Energy balance
Gasification with Fischer Tropsch	D	++	+	+	+
Pyrolysis with upgrading	D	++	?	?	0
HTU with upgrading	W	++	+	+	+

4.3.2 High Thermal Upgrading

High Thermal Upgrading (HTU) is a process to convert biomass into biofuel. It was originally developed by SHELL and currently further developed by the company BIOFUEL BV. The HTU process is a cost-effective route from wet biomass to biofuel. The fuels are compatible with traditional transport fuels and are a "drop-in" replacement, Goudriaan (2003). First, the process is described further and then the products that are produced are discussed.

Process

The process flow of the HTU process is shown in Figure 31. The process starts with the feedstock. However, all lignocellulosic biomass is suitable, the feedstock is the wet algal biomass. The optimal water content in the biomass is 20% (Goudriaan, 2009). Moisture content in algal biomass is 88%, which is more than the optimal condition. More moisture means more volume flow, which affects efficiency. However, it does not affect product quality. In the mass flow calculation, a 20% water content is used. A pump pressurizes the wet biomass to a pressure of 12-18 MPa into a reactor. The reactor has a temperature ranging from 300-350 ºC. So-called biocrude is formed under these temperature and pressure conditions. Several side products are formed as well: carbon dioxide, carbon monoxide, water and some organic residues. The mixture of water and organic residues flows into an anaerobic digester. In the absence of oxygen, bacteria convert these organic residues into methane gas, which is used then to heat the HTU reactor to a temperature of 300-350 ºC. Sufficient quantities of methane gas are produced and no external energy sources are needed for heating.

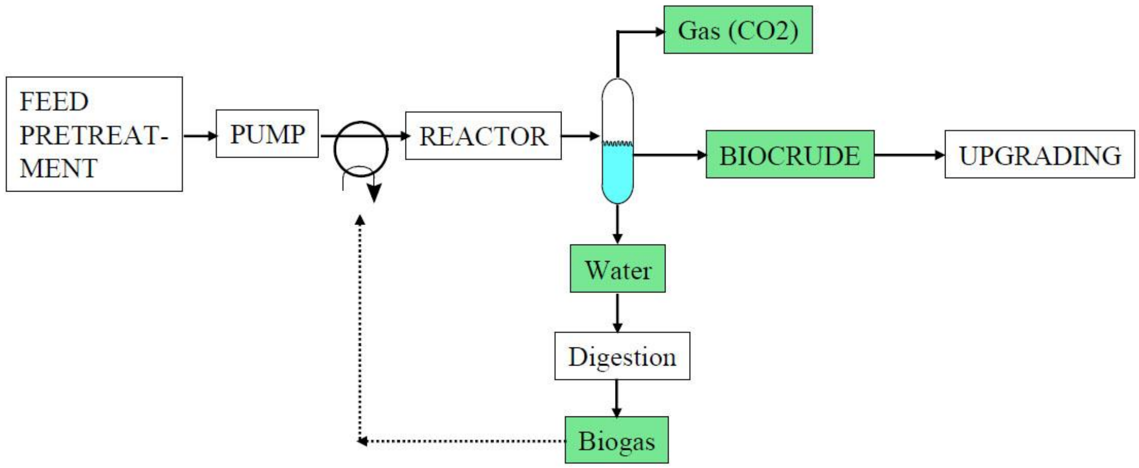

Figure 31 Flow diagram HTU process (Goudriaan, 2003). The biomass is heated and pressurized. Biocrude, carbon dioxide and a mixture of water, nutrients and leftovers are formed. The last fraction is digested anaerobically. The produced methane is used as energy source for the HTU process.

Products

As already explained, five products are formed with the HTU process, namely: biocrude, carbon dioxide, carbon monoxide, organics and water. The products occur in these percentages by dry ash free weight of the macro algae, see Table 7 Goudriaan (2003).

Table 7 Products from HTU process by biomass weight dry ash free.

Products HTU	
Biocrude	45%
CO_2	23%
CO	2%
Organics	12%
H_2O	18%

Not all carbon and hydrogen atoms are converted into biocrude. These atoms are used to remove the oxygen atoms from the biomass. It might be possible to improve the biocrude yields when this process is applied on a large scale. The biocrude being produced has a LHV of 30-35 MJ/kg, and is a mixture of heavy (30%) and light (70%) biocrude. Some contaminants and oxygen molecules still occur in the biocrude. An upgrade process (hydrotreatment) is necessary to remove these contaminants and this will increase the LHV and fuel quality to aviation fuel standards (HRJ).

Yields from algae

So far, algal biomass has not been used as feedstock for the HTU process. The HTU process is expected to be a proper conversion process to turn algae into fuel. As explained in section 4.2, the lower bound yield is set to 12 DAFMT/ha/yr algal biomass. One hectare produces up to 5.4 ton/ha/yr biocrude, see Table 8 for yields.

Table 8 Biofuel yields from 1 ha algae.

HTU			
Yield	12	30	DAFMT/ha/yr
LHV algae	16.5	16.5	GJ/DAFMT
LHV Biocrude	32	32	GJ/ton
Percentage wt biocrude	45%	45%	
Energy supplied HTU	0	0	GJ/DAFMT algae
Energy algae	198	495	GJ/ha/yr
Biocrude	5.4	13.5	ton/ha/yr
Energy biocrude	173	432	GJ/ha/yr

4.3.3 Hydrotreatment

The heavy and light biocrude are not suitable for aviation fuel. Some contaminants such as oxygen, nitrogen, phosphorus etc. still exist in the biocrude. An upgrade is necessary to remove these contaminants. A widely used process in the petrochemical industry is used for this upgrade. Hydro de-oxygenation (HDO) is a hydrotreatment upgrading process which consists of the well-known processes in oil refining of hydrotreating, hydrodesulfarisation and first-stage hydrocracking. The feedstock is fed with hydrogen through a catalyst at a temperature between 200-450 ºC and a pressure of 3-15 MPa. Nutrients and oxygen are removed and, if necessary, the H/C ratio is increased. Hydrogen is needed as feedstock for HDO process. Several hydrogen production methods are optional. A couple of them are: steam methane gas reforming, electrolysis of water or gasification in combination with the water gas shift reaction. The biocrude which is produced can be divided into heavy and light biocrude. The heavy biocrude is hard to upgrade to a fuel, but can be used as co-product for electricity power plants or for hydrogen production. The last option is chosen and the hydrogen is produced from gasified heavy biocrude. The light biocrude gets the HDO upgrade. Yields are mentioned in Table 9 and one DAFMT algae yields 0.29 ton fuel. The fuel being produced with the HDO process must be tested whether the fuel is according to specifications mentioned in section 4.1. The algal fuel with HTU and HDO has not been produced and the specifications cannot be checked. Because HDO is a well-proven technology, the fuel is expected to have similar specifications as HRJ. As said before, ASTM is expected to certify blends up to 50% HRJ and petroleum-derived jet fuel in 2010 (Flight International, 12/10/09).

Table 9 Products HDO process.

HDO			
Yield	12	30	DAFMT/ha/yr
Products			
Naphtha	1.0	2.6	ton/ha/yr
Kerosene	2.4	6.0	ton/ha/yr
Fuel	3.4	8.6	ton/ha/yr
LHV fuel	43.0	43.0	GJ/ton
Fuel per ton algae	0.29	0.29	ton/DAFMT

4.3.4 Delivery

The bio jet fuel is ready for consumption and can be delivered to the airline. In reality, fuel is transported via pipelines from refineries at Rotterdam to Schiphol Airport. In this case, it is assumed that fuel is transported with a truck and trailer over the road to the airport. A typical trailer has a capacity of 35 m^3. The truck has a mileage of 33.2 litre fuel/100 km. The average transport distance from the Rotterdam port to Schiphol is 100 km and a return trip is taken into account. The energy consumption and carbon dioxide emissions are given in Table 10.

Table 10 Aviation fuel delivery data. The fuel is transported with a standard truck and trailer.

Delivery		
Truck		
Distance	100	km
Fuel consumption	33.3	l/100km
Total fuel consumption	66.7	l
Total CO_2 emission	188	kg
Capacity	35000	l
LHV fuel	41.9	MJ/kg
Density	0.805	kg/l
Energy	0.002	MJ/MJ fuel
Emissions	0.007	Kg CO_2/kg fuel

4.4 End-to-end chain

The end-to-end chain consists of three processes. The floating or attached macro algae are cultivated nearshore, the HTU in combination with the HDO process converts them into bio jet fuel and finally the bio jet fuel is distributed and delivered. To visualize this process, the mass flows of cultivation and conversion are given in a flow diagram in Figure 32. Six flows are distinguished, namely: externally supplied energy, algae flow, carbon dioxide flow, fuel flow, nutrients flow and other flows. All these flows are quantified and a product weight overview of the HTU/HDO conversion processes is given in Appendix 3.

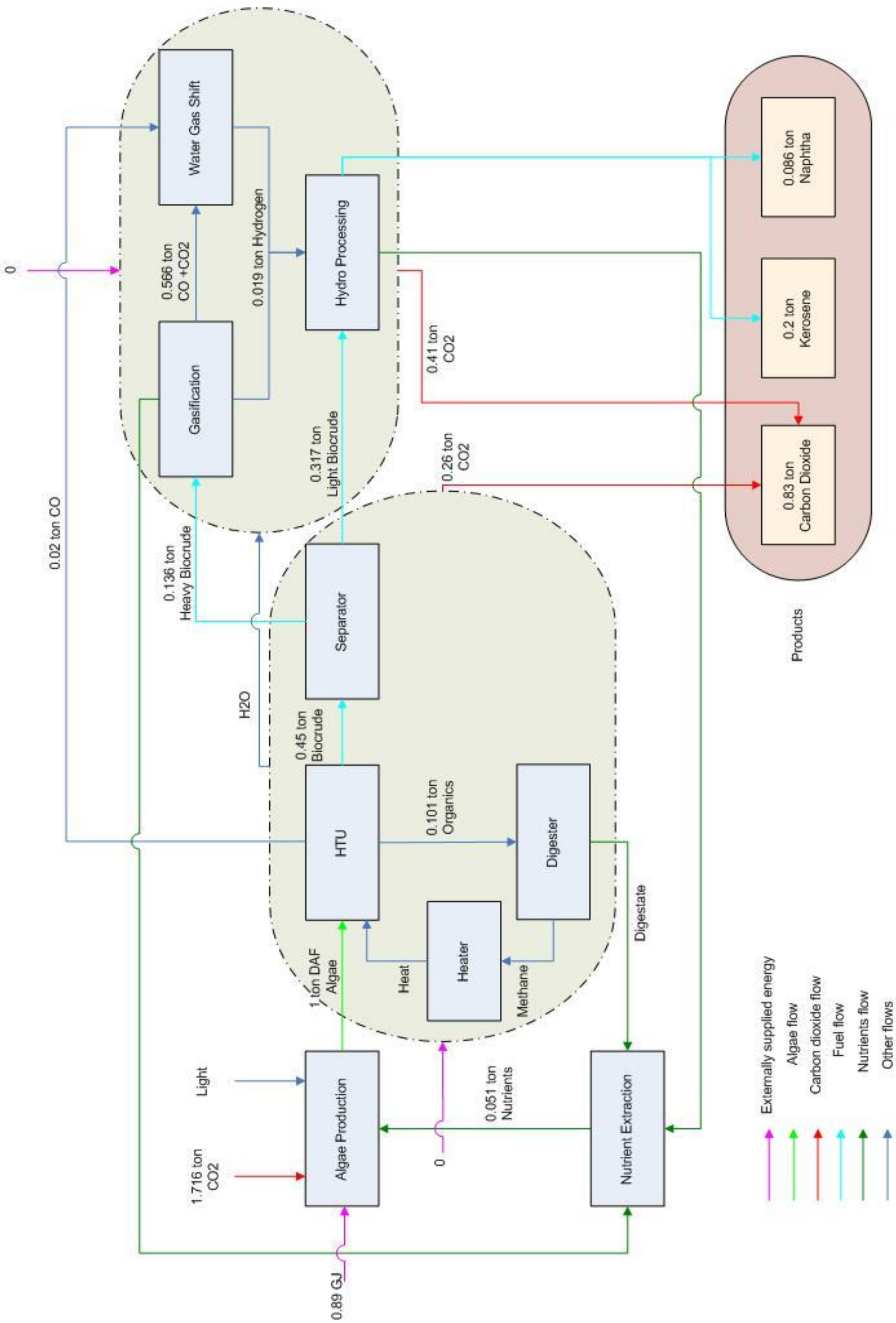

Figure 32 Mass flow in end-to-end chain.

It is possible to produce bio jet fuel from macro algae. There are no technical barriers in the end-to-end chain. Macro algae cultivation for food is done mainly in South East Asia for decades. Plenty of oceans are available worldwide for macro algae cultivation. An issue is whether the yields of macro algae are sustainable. It is if plenty of nutrients are available. Two options are mentioned, cultivate macro algae in nutrient rich waters or apply fertilizers. The former is preferred. The sustainability aspect should be taken into account. Macro algae cultivation should not deplete natural resources such as nutrients or destroy eco-systems such as coral reefs or fish breeding grounds.

The HTU process has been proven on a small scale and the same holds: there are no serious technical barriers. Also, it seems to be that upscaling does not lead to problems. An advantage of this process is that all lignocellulosic biomass can be fed into the HTU process. It is not limited to just macro algae. HTU in combination with HDO is expected to produce high quality HRJ. ASTM is expected to certify blends up to 50% HRJ and petroleum-derived jet fuel in 2010 (Flight International, 12/10/09).

A key issue in the conversion process is the recovery of nutrients. Nutrients become scarce in the current situation. If the nutrients are recovered and turned into fertilizers, these can be applied as fertilizer for macro algae. This will close the loop of the total production process and will make it a renewable and sustainable production.

Concluding, there are no technical barriers to produce bio jet fuel. However, the theory will differ from practice sometimes. There is just one way to prove if it works and that is just start the production. Bio jet fuel production might face problems, but these can be solved.

5 Feasibility end-to-end chain

After defining the end-to-end chain, the feasibility is analysed. It is feasible if all of these four items are met: renewable and sustainable production of macro algae, a positive energy balance, reduced carbon dioxide emissions and the bio jet fuel should be economically viable.

The questions asked in this section are:

- What is the energy returned on energy invested (EROEI) of macro algae based biofuel? (section 5.1.1).
- How much carbon dioxide is emitted in the end-to-end chain? (section 5.1.2).
- Are macro algae economically viable in the future? (section 5.2).
- Which actions can be taken to accelerate the energy transition? (section 5.2.4)

5.1 Energy and carbon dioxide balance

A summary of each process is given, including all relevant information about the energy use and carbon dioxide emissions. It is important to note that all numbers mentioned are calculated for a macro algae yield of 12 DAFMT/ha/yr. Later on, the energy balance and carbon dioxide emission in the end-to-end chain are summed up for several scenarios.

Seeding
The algae are planted nearshore in cultivation areas. The plants are spread out from a ship in the cultivation area. The aim is to plant the algae once and the algae continue growing forever. Replanting is avoided and thereby energy is saved. Due to the lack of cultivation experience in the North Sea, the energy use is hard to predict. In the best-case scenario, algae are seeded once. In the worst-case scenario, algae must be replanted after each harvest. In these calculations, it is assumed algae are replanted every 10 years. The ship has the same energy consumption as the harvester. This will be further explained in the harvesting section.

Fertilizing
As said before, algae need nutrients to grow mainly nitrogen and phosphorus. Fertilizers are currently produced for use in agriculture, and are used to increase yields. Not all fertilizers which are applied are absorbed by the crops (Chen, 2008). A part flows via canals and rivers into the sea. When yields are 12 DAFMT/ha/yr and with the chemical composition from Table 3, one hectare needs 373 kg nitrogen and 65 kg phosphorus annually. When these amounts are supplied, not all of these nutrients are absorbed by the algae. The behaviour of nutrient flows is unpredictable and in these calculations, it is assumed these amounts are supplied per hectare. The average energy consumption and carbon dioxide emission for fertilizer production are 40.3 MJ/kg and 5.29 kg CO_2/kg for nitrogen and for phosphorus 3.4 MJ/kg and 0.22 kg CO_2/kg (Kongshaug, 1998). This results in an energy use of 4.46 MJ/kg_{fuel} and a carbon dioxide emission of 0.58 kg CO_2/kg_{fuel}.

Harvesting

The algae are harvested by the harvester described in the previous section. The harvester is powered by a diesel driven engine. The engine burns 4.000 kg fuel and harvests 229 tons algal fuel daily. This is an energy use of 0.754 MJ/kg_{fuel}. The emissions are equal to 0.061 kg CO_2/kg_{fuel} for a yield of 12 DAFMT/ha/yr. See also Appendix 6 for all relevant information of the macro algae harvester.

Transport

The wet algal biomass is transported into the barges. Several barges are combined and are pushed by one tug to the conversion facility. The energy use for this transport is 1.52 MJ/kg_{fuel}. The tug is also powered by a diesel engine and the emissions are 0.124 kg CO_2/kg_{fuel}.

Extraction and upgrading

The wet algal biomass is pressurized ranging from 12-18 MPa and heated to 300-350 ºC. The major part of the energy is needed for heating and comes from the biomass itself. The organic leftovers are anaerobically digested and the formed methane gas is used for heating. The energy requirement for pumps and pressurizing are ignored. The energy is generated internally and the carbon dioxide emissions are zero.

Hydro de-oxygenation is a process widely used in the refining industry. The energy use in this process depends on the amount of contaminants and whether the H/C ratio has to decrease. The energy use and carbon dioxide emission largely depends on the amount of supplied hydrogen. Large amounts of hydrogen are required. When hydrogen is made from methane gas, the energy used and carbon dioxide emissions for upgrading biocrude are expected to be 0.29 MJ/MJ_{fuel} and 0.87 kg CO_2/kg_{fuel}, respectively, which is substantial. That is why gasification of the heavy biocrude is chosen. No external energy has to be supplied into gasification. In both HTU and HDO processes carbon dioxide is formed, which can be emitted into the atmosphere. A second possibility is to capture carbon dioxide and store it (CCS). Currently, research is going on to capture the CO_2 from coal-fired power plants (Biello, 2009/2010) and this might be possible for the HTU/HDO process. This will be further discussed in section 5.1.2.

Transport

The fuel is transported with a diesel truck to the airline. A typical truck consumes 33.3 litre/100 km. The energy use is equal to 0.082 MJ/kg_{fuel} and the emissions are 0.007 kg CO_2/kg_{fuel}.

All this data is visualized in Figure 33, in which the carbon life cycle is given. In each of the eight processes are mentioned the carbon dioxide absorption/emission, the consumed energy and the time it takes.

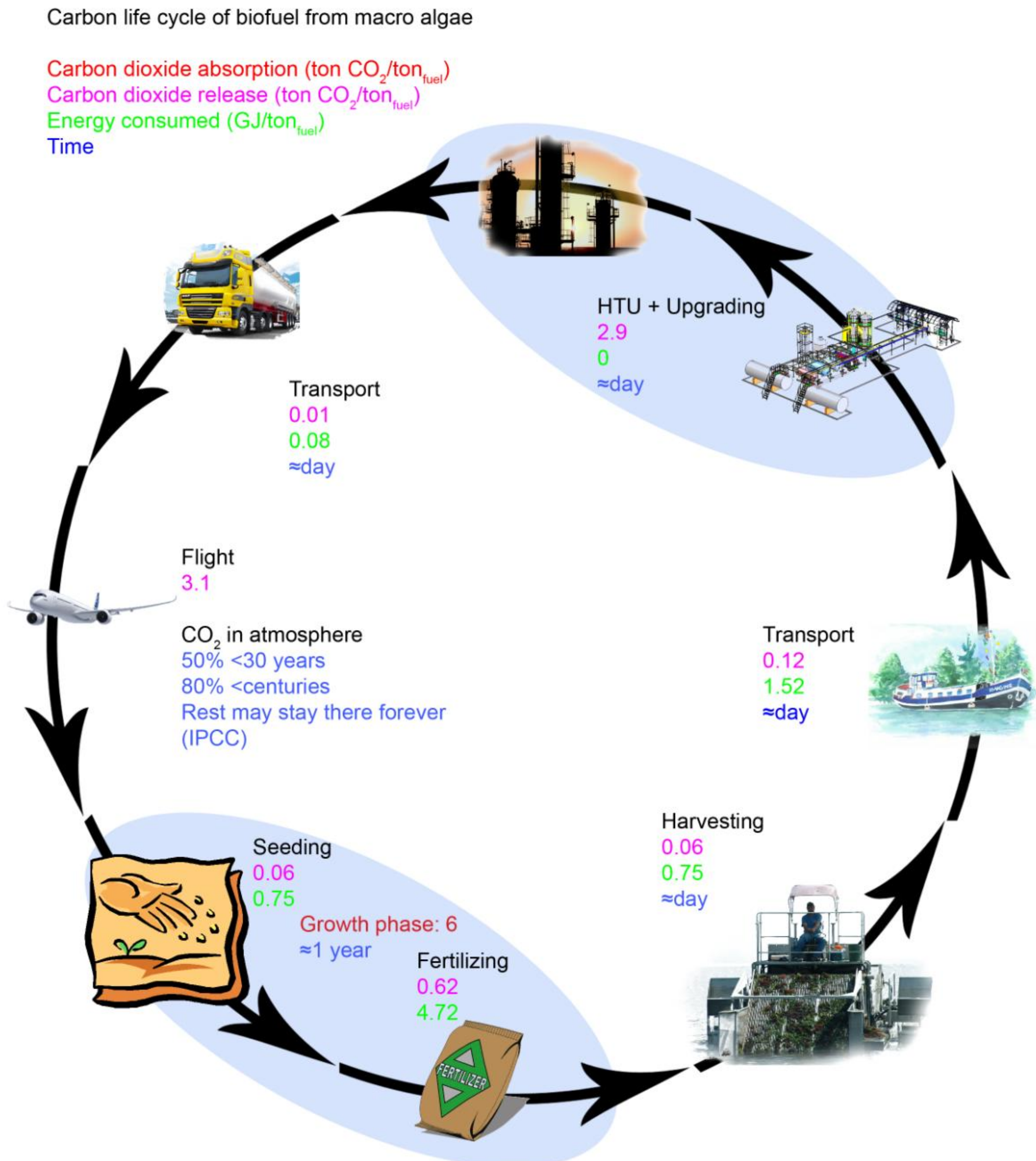

Figure 33 Life cycle of bio jet fuel from macro algae with a yield of 12 DAFMT/ha/yr. The carbon dioxide emission/absorption, energy consumed and time for each process are given.

5.1.1 Energy balance

The external energy which is supplied to the processes is discussed in the introduction of this section. One of the requirements from the research question is a positive energy balance. The formula for the total externally supplied energy (ese) is:

$$E_{ese} = \sum E_{ese,process}$$

The energy balance (EB) is defined according to energy returned on energy invested (EROEI).

$$EROEI = \frac{E_{\mathrm{Pr}oduced}}{E_{ese}} - 1$$

A positive energy balance means more energy is produced than energy is supplied from the outside. In case of energy returned on energy invested: EROEI>0. The aim is to get an EROEI as large as possible.

The external energy supplied to the total process is visible in Figure 34. Two sets are made for a yield of 12 and 30 DAFMT/ha/yr, respectively. In both cases, fertilization is taken into account which is substantial. A second set is made without taking fertilizer into account.

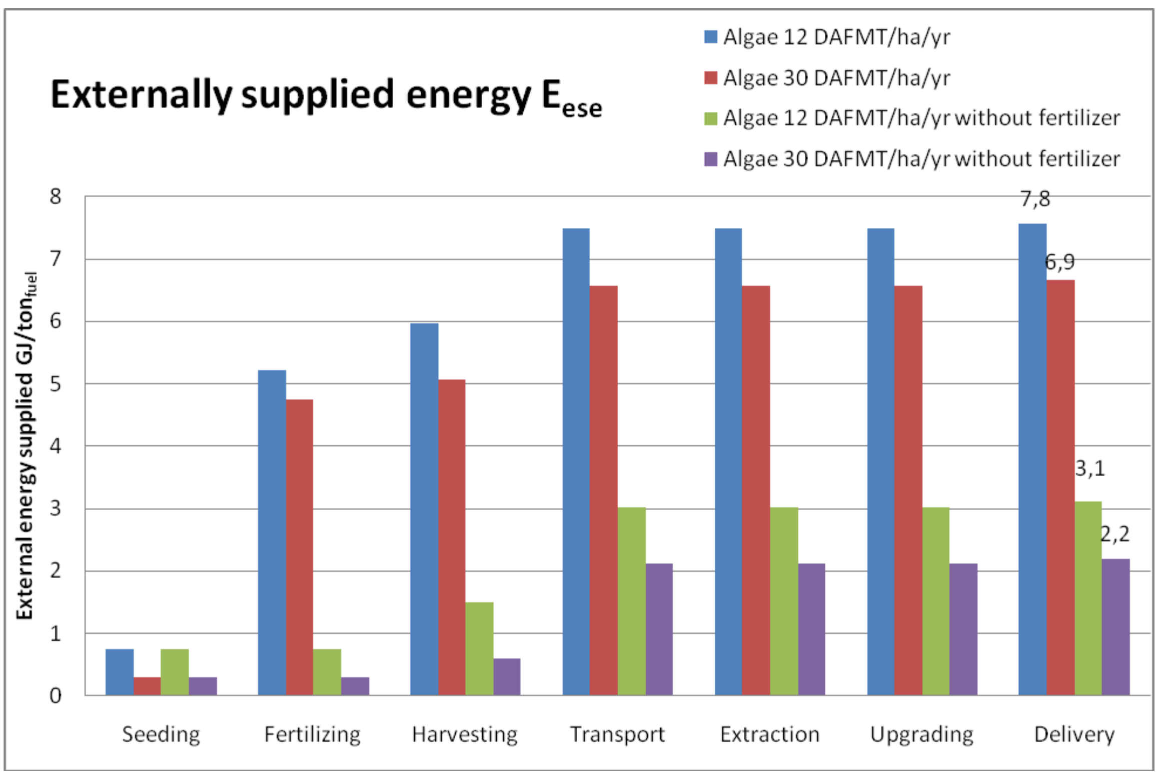

Figure 34 Cumulative external energy supplied in the end-to-end chain.

The energy returned on energy invested is calculated afterwards. These values are visible in Figure 35. The EROEI is calculated for an algae yield of 12 and 30 DAFMT/ha/yr and fall in the range of 4.5-5.2. These values are compared with current EROEI of corn based ethanol, sugarcane ethanol, rapeseed biodiesel and fossil fuel. Currently, sugarcane ethanol is most productive of all, even more productive than fossil fuel production. EROEI of rapeseed biodiesel and corn ethanol are least productive of all. Corn based ethanol comes close to 0.

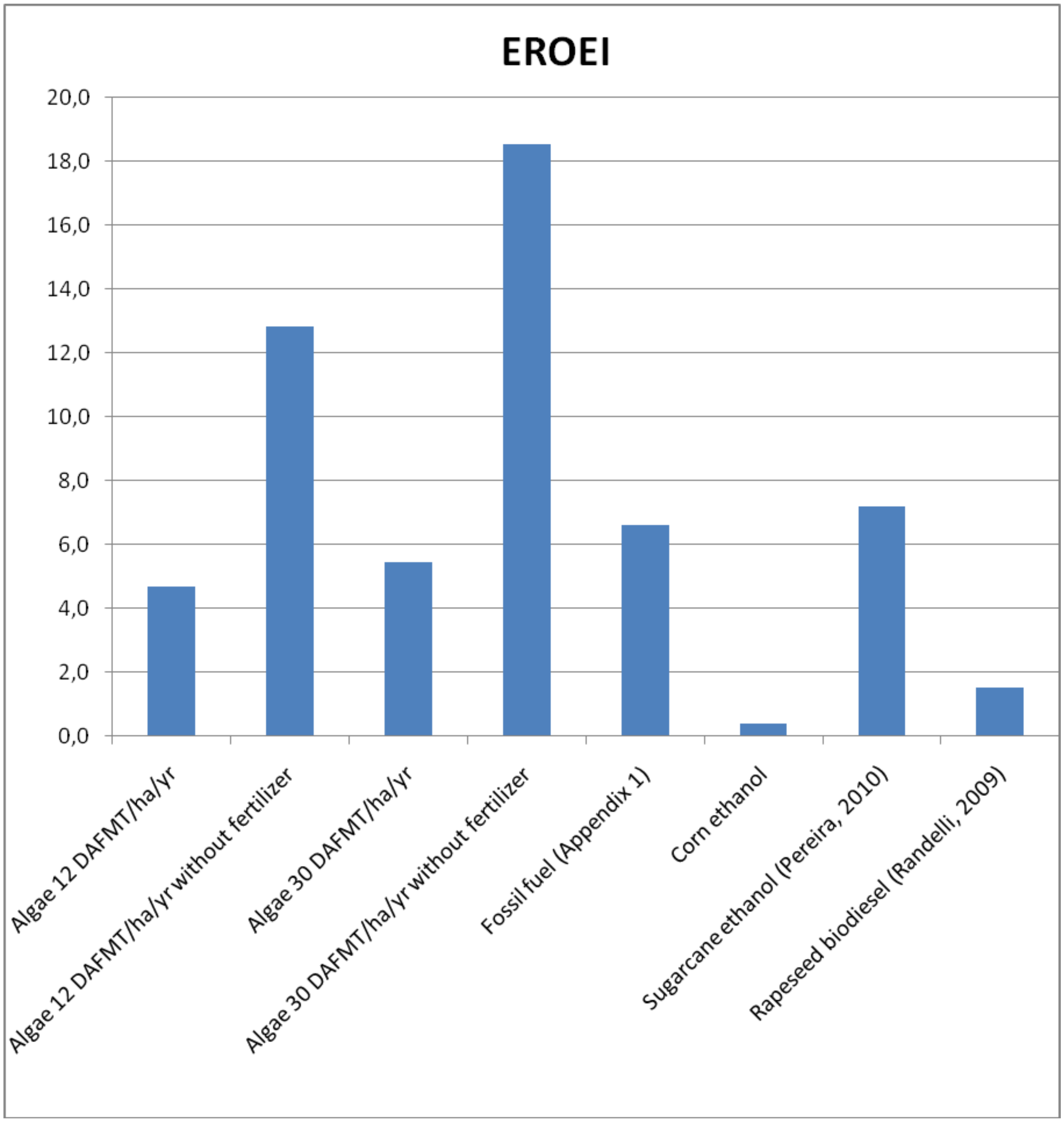

Figure 35 Energy returned on energy invested (EROEI).

5.1.2 Carbon dioxide balance

The carbon dioxide emissions in the end-to-end chain are discussed in this section. Several scenarios are given. A macro algae yield of 12 DAFMT/ha/yr is assumed here. It appeared that the cumulative emissions do not differ significantly (Appendix 7) with a yield of 30 DAFMT/ha/yr. The two scenarios for carbon dioxide emissions are for a normal situation and with carbon capturing and storage. The cumulative carbon dioxide emissions are given in Figure 36. Every scenario starts with the absorption of 6 kg $CO_2/kg_{jet\ fuel}$ by the macro algae. In every following process, carbon dioxide is produced and emitted. This obviously depends on whether fertilizer is applied and carbon dioxide is captured and stored. It must be noted that it is unsure if it is possible to capture the carbon dioxide from the HTU/HDO process. Pilot projects are running for CCS from coal-fired power plants (Biello, 2009/2010). Secondly, there are unknowns about storing carbon dioxide regarding to safety and capacity (Biello, 2009/2010). The energy it takes to capture and store carbon dioxide is not taken into account. In the first scenario (blue column), the carbon dioxide emission are reduced by 75%. If no fertilizers are applied, the emissions could be reduced by 90% (not mentioned in figure). In the second scenario (red column), the end-to-end chain is a net carbon dioxide absorber thanks to carbon dioxide capturing and storage.

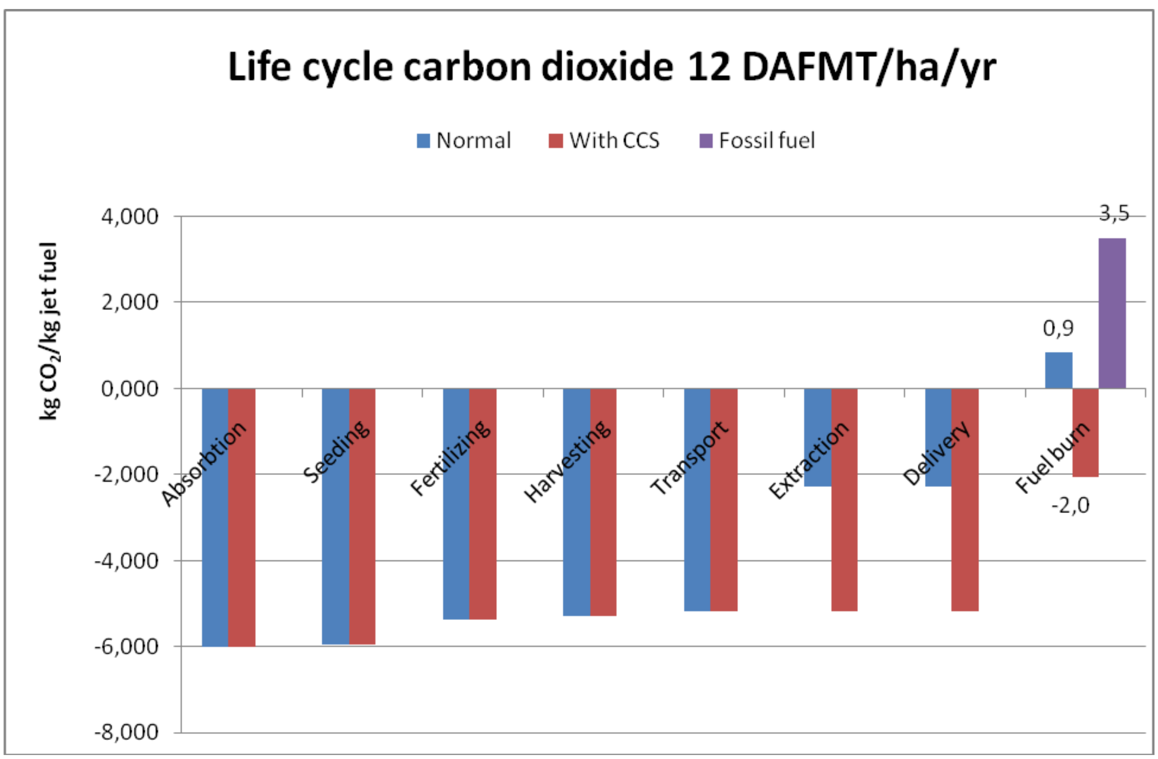

Figure 36 Cumulative carbon dioxide emissions in the end-to-end chain.

Another point of discussion is the flux of carbon between the atmosphere and the ocean surface. In Figure 33 the carbon life cycle is given, where it is assumed carbon is naturally absorbed by the ocean surface. There is a natural flux between the atmosphere and ocean surface, see Figure 37 (IPCC, Metz 2007). Carbon is absorbed by macro algae from the ocean surface, but the carbon is emitted into the atmosphere. The question is whether the natural flux is sufficient. Several researches note about it. IPCC (Metz, 2007) state anthropogenic (human made) carbon dioxide is absorbed from the atmosphere: 50% within 30 years, 80% within centuries and the rest may stay in the atmosphere forever. Watson (2009) is tracking the variable North Atlantic sink for atmospheric carbon dioxide. In his research is concluded: "net increase of the atmospheric concentration is only half what it would be if all the CO_2 is remained in the atmosphere". Anthropogenic CO_2 is absorbed by biomass and oceans. "CO_2 uptake by oceans reduces pH of surface

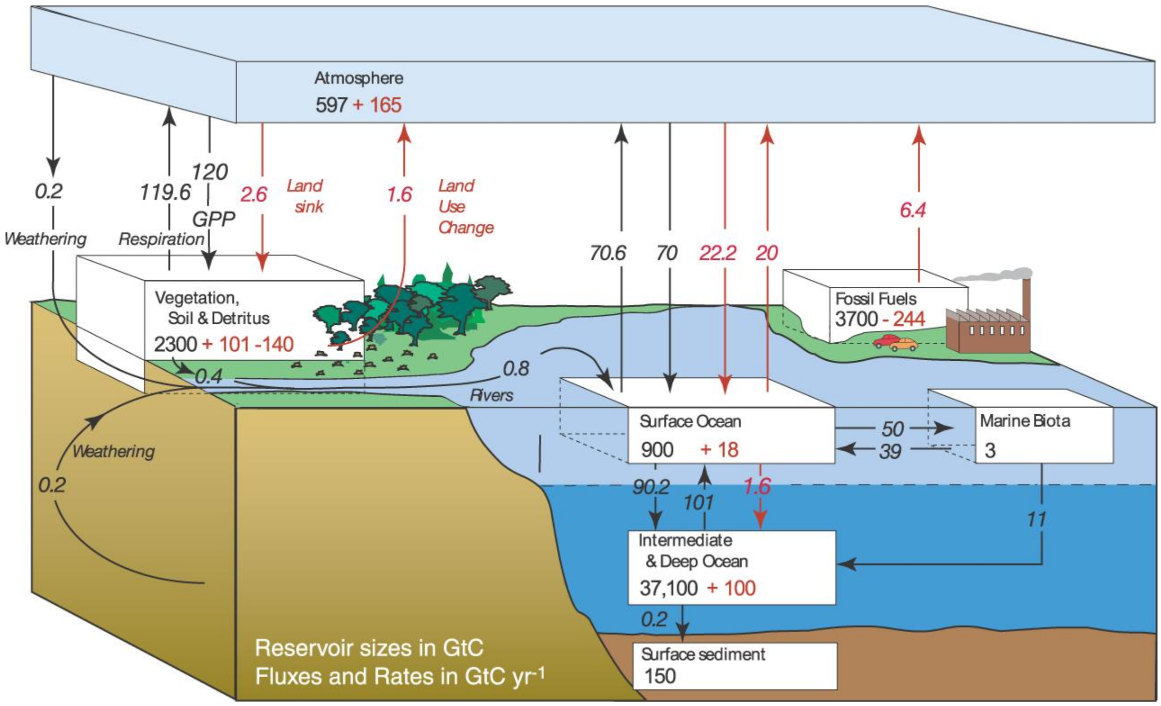

Figure 37 Global carbon cycle (IPCC, Metz 2007)

waters, an acidification that is expected to have appreciable effects on the marine biota over this century". Scientists are not sure about the lifetime of anthropogenic carbon dioxide in the atmosphere. Besides that, it is not known what will happen if large quantities of carbon from the ocean surface are extracted. Two obvious options are carbon which is extracted will be supplied from atmospheric carbon dioxide. Secondly, carbon is supplied from the deep ocean, which is undesirable. With these unknowns, it is impossible to state if the life-time of atmospheric CO_2 is shortened.

The European Union is implementing EU ETS (European Trading Scheme). It is a policy to reduce carbon dioxide emissions by trading. Aviation is involved as well and will start in 2012 (Official journal of the European Union, decision 2009/339/EC). It is assumed that the carbon dioxide emissions in the life cycle of fossil fuel and biofuel are reduced from 3.5 to 0.9 kg $CO_2/kg_{jet\ fuel}$. The future price of carbon dioxide is unclear. If the price is set to €20/ton CO_2, this will turn into a price of €70/ton fossil jet fuel and €18/ton bio jet fuel, a difference of €52/ton fuel.

5.2 Economical viability

Much research has been done into algae based biofuel. The last time was during the second oil crisis in the 1980's. Cost estimations were performed and biofuel seemed to be competitive at high energy-prices. The research and biofuel production were abandoned when the oil prices collapsed. Guiry (1991) stated, "macro algae will need to wait until the next energy crisis". Bio jet fuel is economical viable if it is demanded for example from defence, airlines or it is promoted by legislation. A hybrid approach is used to determine the production costs of biofuel. Both approaches have their limitations and could complement each other. The first approach is based on experience curves (section 5.2.2). Experience curve will show how fuel production costs will evolve. The second is based on bottom-up approach (section 5.2.3). The production costs are calculated in each chain and summed up. Both approaches will show and confirm the cost-price for bio jet fuel now and in the future. Several actions such as a feed-in system and legislation to promote biofuel are possible to accelerate the transition from fossil fuel to bio jet fuel and these actions are discussed in section 5.2.4.

5.2.1 Historical background information price and demand jet fuel

Demand for jet fuel

The aim is to know what the demand is for aviation fuel. With that in mind, two regions are defined. With this knowledge, the total algae production and the cost price of biofuel can be determined.

- Global demand: total consumed aviation fuels globally.
- Demand from the Netherlands: all aviation fuels sold in the Netherlands to airlines for international use.

Worldwide aviation fuel demand grew to an all time high record of 241 million tons in 2007 according to EIA, see Figure 39. A small fraction is consumed for Dutch air transport. Data about fuel demand in the Netherlands is gathered and plotted in Figure 38. Demand NL means the total kerosene delivery in the Netherlands for international aviation (CBS, 2010). Unfortunately, no data was found about the aviation fuel consumption of Dutch residents. As a result, demand in the Netherlands and global demand are further used in this research.

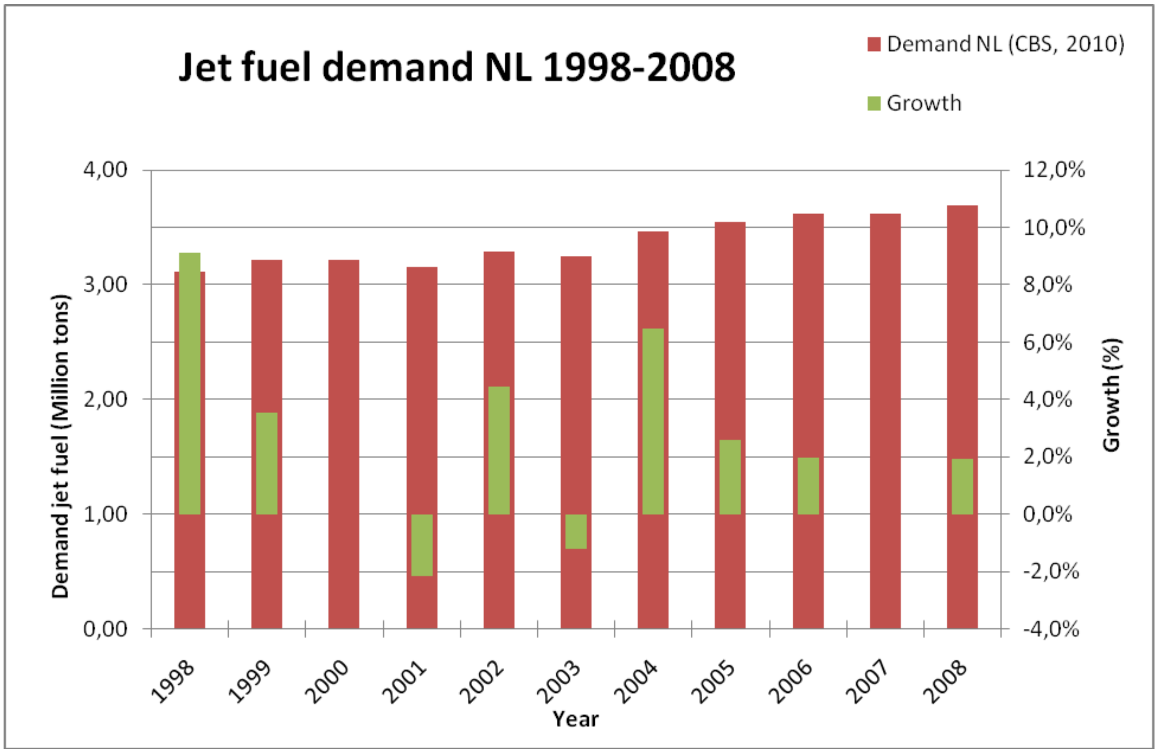

Figure 38 Fuel demand in the Netherlands 1998-2008, (CBS, 2010). The growth per year is calculated and the average growth was 2.4% in the time-frame 1990-2008.

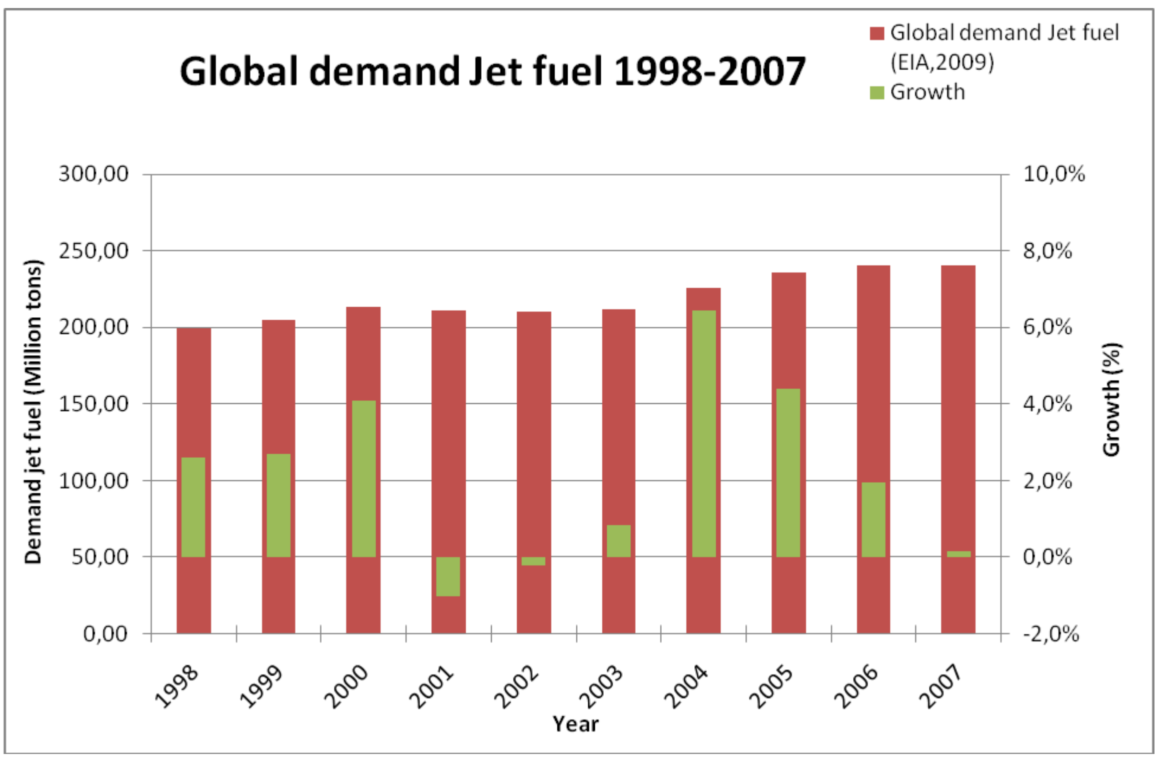

Figure 39 Global demand jet fuel 1998-2007 (EIA 2009). The average growth was 2.2 % in the time-frame 1990-2008.

Aviation fuel price

Fuel is a major expense for airlines. The percentage fuel expenses of the total expenses of two airlines are analysed. Two airlines are chosen with different business models, namely, Air France-KLM and Ryanair. Data is taken from the last five book years from 2004 until 2009. The percentage fuel expenses/total expenses are given in Figure 40. It appears that the fuel expenses of the total expenses over 2004-2009 of Air France-KLM and Ryanair were 19% and 38% respectively. A fluctuating fuel price affects the costs of Ryanair more than Air France-KLM. These numbers are used further to determine the effect of biofuel on the fuel expenses.

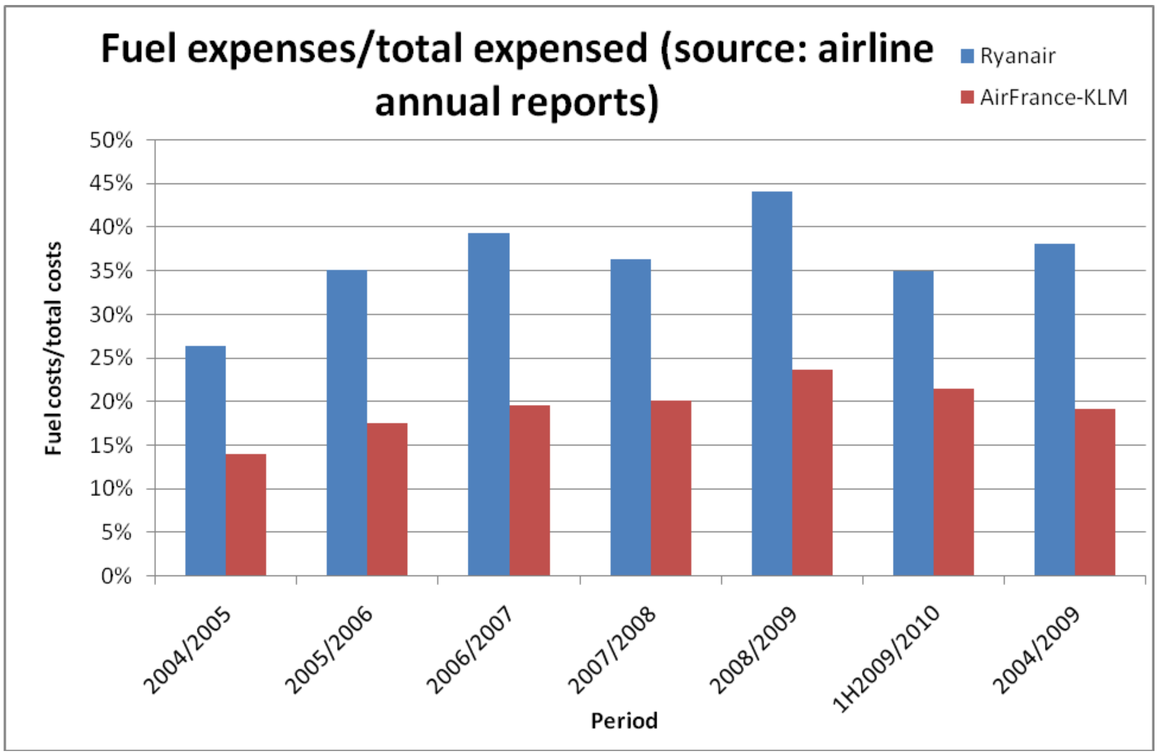

Figure 40 Fuel expenses per total expenses of two airlines. Data is gathered from the airline annual reports. Both airlines have a different business model. The percentage fuel expenses per total expenses are substantially larger at Ryanair than Air France-KLM.

Historical data about the aviation fuel prices is gathered and is plotted in Figure 41 (www.airliners.org, 2009). Two peaks are visible in the graph the first one during the eighties and the second one in 2008. The oil price has been steady between these two peaks with the lowest point in 1999. It is clear that it is impossible forecast the price of jet fuel with regression lines. The purple line is a linear regression line that has an R^2 of 0.25 which is a poor fit. The IEA forecasted a fuel price in 2015, 2020 and 2030 which are mentioned in Figure 41. A margin is added to get the forecasted price of jet fuel. A linear line (light purple) is plotted through these numbers. It is assumed that the price of jet fuel will follow this trend and this is used in this section later on.

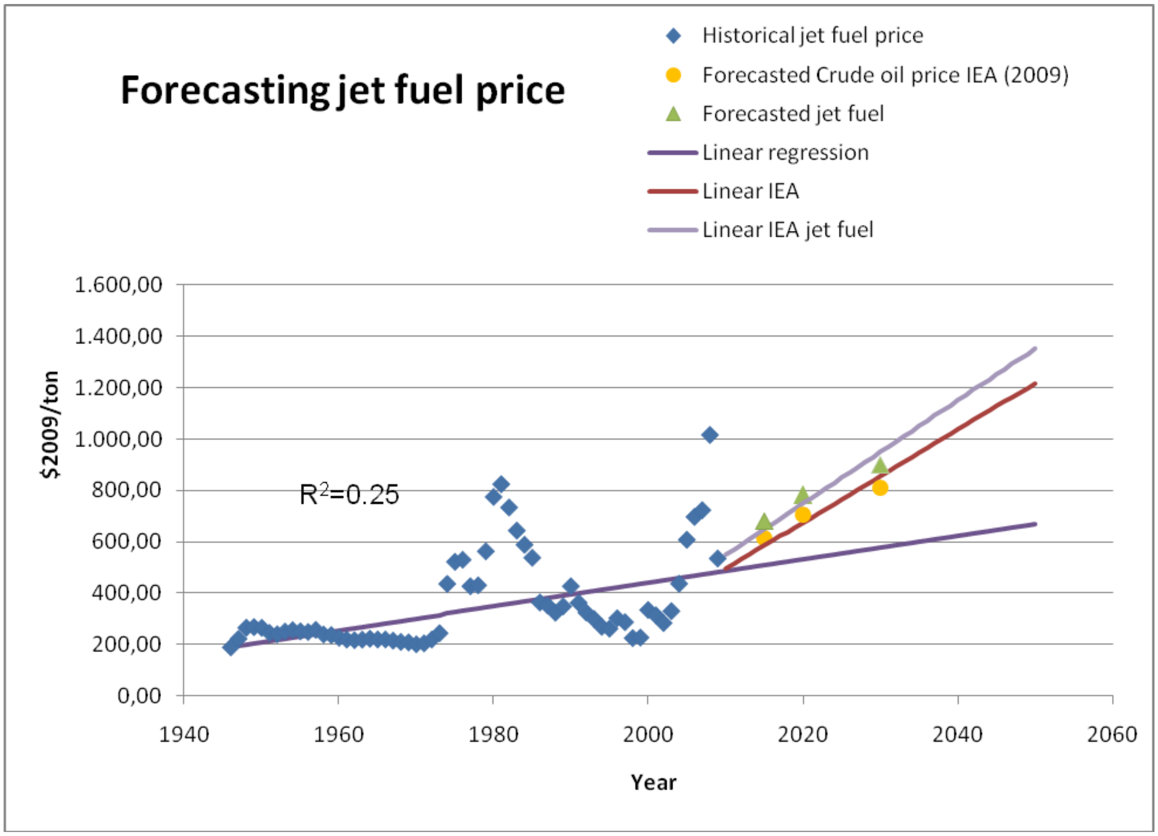

Figure 41 Forecasting jet fuel price.

5.2.2 First approach: Experience curves

In the first approach, the cost price of bio jet fuel is determined by experience curves. The experience curves mean the price declines with a constant factor (progression ratio) if production doubles. These can be used to forecast production costs, not to forecast prices. Before the cost price of bio jet fuel is dealt with, several other energy systems are discussed. Several energy supply technologies are researched on experience curves by Junginger (2008). Each experience curve can be plotted in a graph and usually both axes are on a logarithmic scale. The x-axis represents installed capacity and the y-axis represents the price. The experience curves of electricity production systems are given in Figure 42. For example, photovoltaics and onshore wind energy have a progression ratio (PR) of 79.4% and 85%, respectively. Figure 42 also shows that the PRs do not decline after 2002. Junginger (2008) explains this by a combination of increasing demand for these technologies, rising raw material prices and rising prices of fossil reference technologies. Recent price updates until 2009 are not included in the graph. The price of photovoltaics declined by 50% by end of 2009, says New Energy Finance (press release 23 November 2009). If this is included, the experience curve will continue.

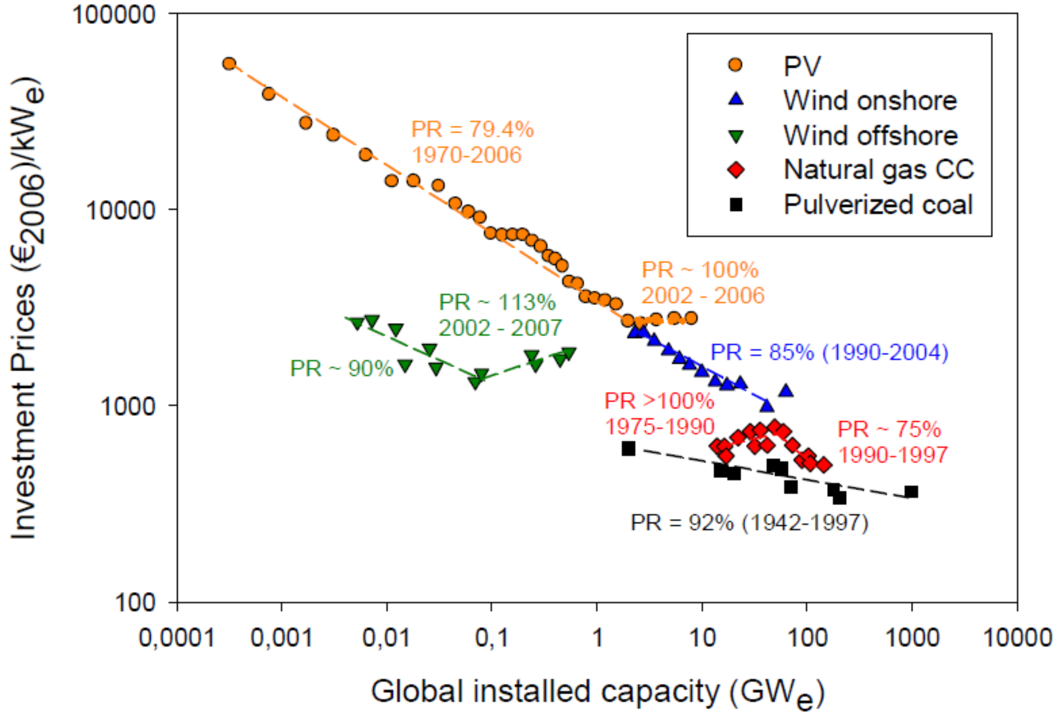

Figure 42 "Comparison of historic experience curves of energy supply technologies. Note that all (renewable) energy technologies investment prices are increasing, from 2002 onwards leading to PRs>100%. This is likely to be caused by a combination of increasing demand for these technologies, rising raw material prices, and rising prices of fossil reference technologies" (Junginger, 2008).

Another energy supply is researched as well. Sugarcane is cultivated in Brazil for ethanol production. The progression ratio for sugarcane (production) and ethanol production (conversion) is calculated, see Figure 43. These are 68% and 81%, respectively. This biofuel programme has similarities with bio jet fuel production from algae. The aim in both projects is to make biofuel. In both projects, biomass is cultivated and converted into fuel. This confirms that the price of bio jet fuel from macro algae declines too when production increases.

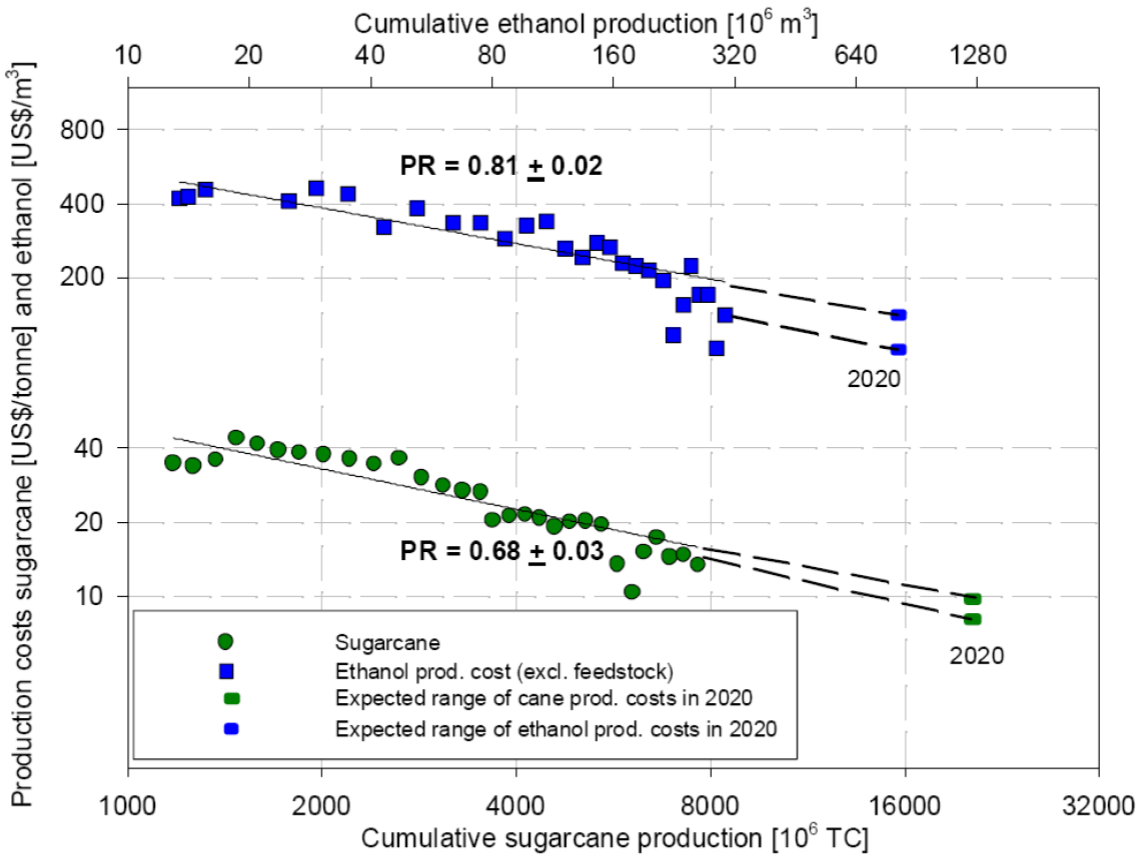

Figure 43 "Experience curves for sugarcane production costs and ethanol production costs in Brazil between 1975-2005, and extrapolation to 2020" (Junginger, 2008).

Experience curves also have limitations. All limitations are summed up in Appendix 10. The main limitations are mentioned below:

- It does not include effects on increasing raw material prices.
- Geographical constraints.
- Legislation could lead to strong demand and unbalanced supply and demand.

After the brief introduction into experience curves, this theory is applied to macro algae. The production costs for algae fuel are forecasted. The algae market prices have already been discussed in section 4.2.1. Exponential trend lines are plotted through annual production and annual market price. The progression ratio (PR) is determined from these trend lines by using the statistical software SPSS. The PR of algal biomass is equal to 0.59±0.013 in the time frame 1984-2007, see Figure 44. The R^2 is 0.96, which means the regression line is a high quality fit.

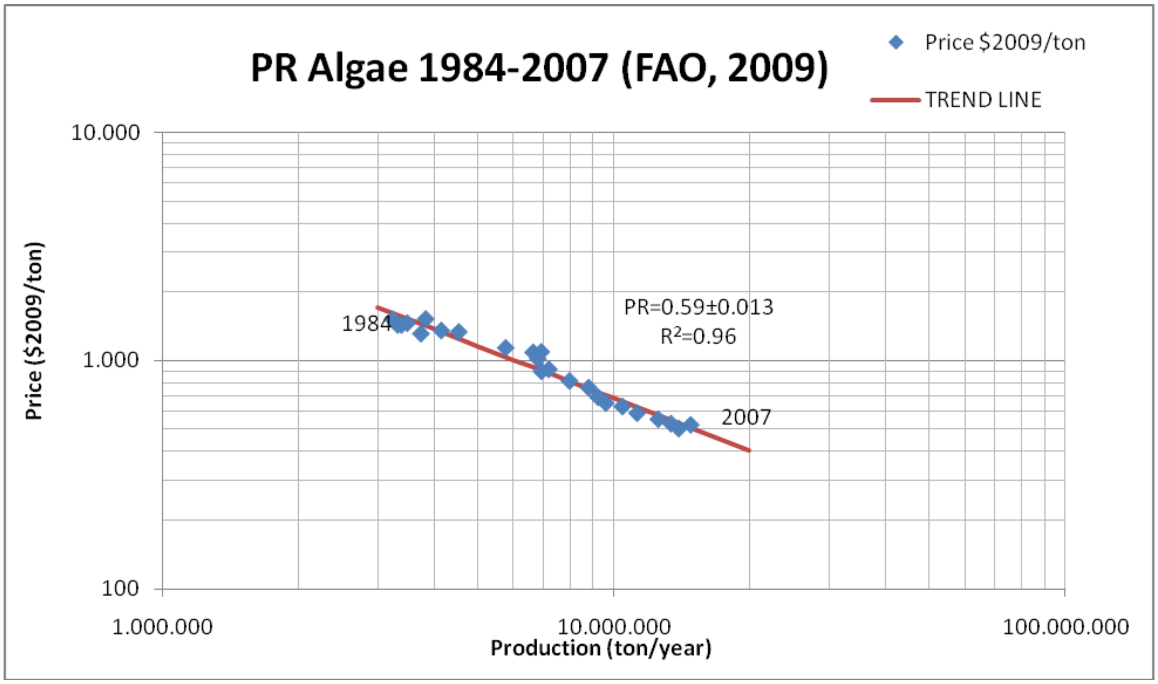

Figure 44 Progression Ratio algae price 1984-2007 (FAO, 2009). The progression ratio is calculated with statistical program SPSS. PR of macro algae is 0.59±0.013.

The production of macro algae will grow substantially when aviation fuel is produced from it. Global demand was over 241 million tons of aviation fuel in 2007. One wet metric ton algae produces up to 0.025 ton biofuel from which 70% bio-kerosene and 30% bio-naphtha (section 4.1). It is assumed both products are used for aviation fuel. Ten billion tons wet algae are needed to fulfil the total aviation fuel demand.

The trend line in Figure 44 is projected to a global production of 10 billion tons wet algae (red line), see Figure 45. The algae price is divided by 0.025 to get the feedstock price (blue line). The total cost price for aviation fuel consists of feedstock costs and conversion costs. The conversion costs will probably decrease when production increases. The progression ratio of the HTU/HDO process is not known. It is known that conversion costs for a small or large facility are 602 and 241 US\$/ton$_{fuel}$, respectively (Goudriaan, 2003). The conversion costs are added to the feedstock costs. This results in the total fuel costs (green line). Other costs such as transport are neglected. In the start-up phase, conversion costs are a small fraction of the total fuel price. The feedstock and conversion costs are 16.602 and 602 \$/ton$_{fuel}$ respectively. When production increases, conversion costs drop rapidly to 241 \$/ton$_{fuel}$. The green line in Figure 45 represents the predicted fuel price. When production hits 10 billion tons wet algae, the total fuel price is predicted to be 393 US\$2009/ton$_{fuel}$. Today's price of jet fuel is about 700 \$/ton$_{jet\ fuel}$. From this approach, algae based biofuel becomes economically competitive with fossil fuel.

The calculations explained above are summed up:

$$\text{Algae Fuel}\left[{}^{\$}\!/_{\text{ton}}\right] = Feedstock_{tonFuel}\left[{}^{\$}\!/_{\text{ton}}\right] + Conversion_{tonFuel}\left[{}^{\$}\!/_{\text{ton}}\right]$$

$$Feedstock_{tonFuel}\left[\$/\text{ton}\right]=\frac{a\left[\$/\text{Ton Wet Algae}\right]\cdot PR^{b}}{c\left[\text{Ton Fuel}/\text{Ton Wet Algae}\right]}$$

a = Initial price ($/ton wet fuel)
PR = Progression Ratio
b = doublings of production
c = constant = 0.0253 ton fuel/ton wet algae.

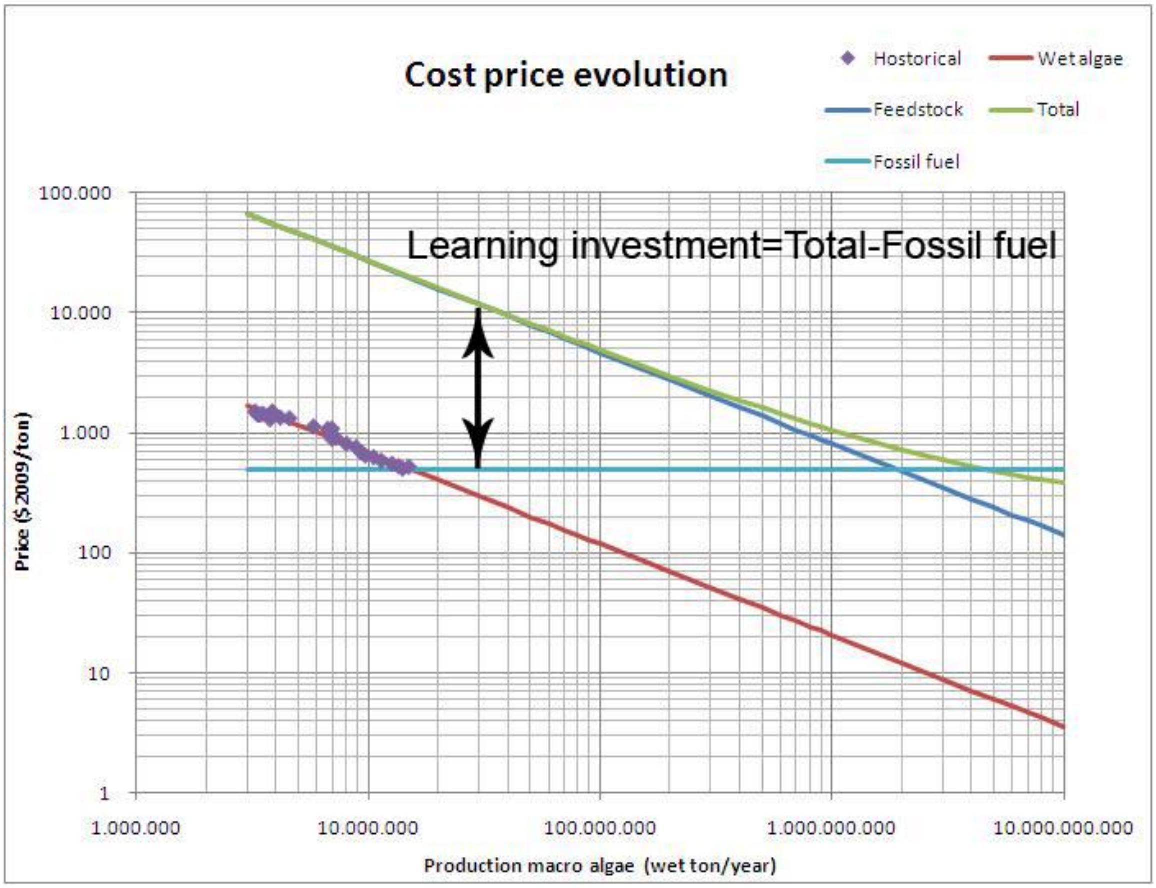

Figure 45 Forecasting the cost price of bio jet fuel based on a PR=0.59 of macro algae. The red line is the production cost of macro algae (wet). The purple dots are the historical prices of wet macro algae. The blue line represents the feedstock price per ton bio jet fuel. The conversion costs are added and this results in the total cost of bio jet fuel (green line).

The current price of bio jet fuel would be roughly 17.000 $2009/ton, see Figure 45. This is substantially more than the fossil fuel price of 700 $2009/ton. The difference will get smaller in the future when bio jet fuel prices go down and fossil fuel prices go up. The fossil fuel price is set to $700/ton in Figure 45. At a certain point, both prices will cross each other. Until this crossing point, the price gap is called learning investment or investment and needs to be paid. In section 5.2.4, the investments are discussed further.

5.2.3 Second approach: Bottom-up

In the previous section, it was determined how fuel price will evolve with an experience curve. In this section the price of biofuel is determined with a bottom-up approach. The cost prices for the seven processes in the end-to-end chain are determined and summed up. The cost price per process is mainly based on earlier research and for an macro algae cultivation area of 200 km^2. The price is determined for two different scenarios. These have an algae yield of 12 DAFMT/ha/yr and 30 DAFMT/ha/yr with biofuel yields of 3.4 and 8.6 ton_{fuel}/ha/yr, respectively. The calculations below are worked out for a yield of 12 DAFMT/ha/yr. The complete calculations are in Appendix 9. This approach is compared with the experience curve in the previous section. All values are in €2009, later on in $2009 by assuming an exchange rate of $1.40/€.

Seeding
Seeding is supposed to happen once in a number of years. The floating or attached macro algae species are seeded near shore. Replanting is assumed to happen once in ten years. This must be researched if this is possible. Seeding costs are 9.710 €/ha, Bird (1987) and the cost of capital is assumed to be 10%. The costs for seeding are 567 €/ton_{fuel}.

Fertilizing
It has to be determined whether fertilizing is necessary. Obviously, the costs are zero when fertilizing is not necessary. If fertilizing appears to be necessary, the net uptake is assumed. The price for nitrogen and phosphate fertilizers was 432.5 €/ton in 2009, (Agrifirm, 2009). The fertilizer costs are 58 €/ton_{fuel}.

Harvesting
Harvesting equipment explained in section 4.2 is used for harvesting. The harvester is capable of harvesting algae with a fuel yield of 228 ton_{fuel}/day. Harvesting costs are determined by four values. These are depreciation of the harvester, maintenance costs, labour costs and fuel costs. The purchase price is assumed to be €5 million and is depreciated in ten years. This is based on general rules in maritime engineering. The empty weight is a third of the payload. The payload is 5.000 tons for the algae harvester. The purchase price is about €3/kg empty weight. From these basic rules follows a rough purchase price of €5 million (Hekkenberg, 2009). The maintenance cost is 1% of the purchase costs of the harvester per year. A six men crew is required and they cost 50.000 €/yr each. The fuel consumption is 4.000 kg per day. The diesel price is assumed to be €1/liter. The expenditures for fuel are €5.000 per day. The total costs for harvesting amounts to 42 €/ton_{fuel}.

Transport to conversion facility
One tug is sailing between the harvesting location and the conversion facility. The tug is estimated to cost €1 million and is depreciated in ten years. The annual maintenance costs are also 1% of the capital costs. The crew consists of two members who cost 50.000 euro's per year. The barges are roughly estimated to cost €9 million in total. The total costs for transport are 76 €/ton_{fuel}.

Extraction and upgrading
The extraction and upgrading costs are combined. The costs have been calculated by Goudriaan (2003). A distinction is made between the first plant (baseline) and a future plant (advanced). The costs are 430 and 172 €/ton$_{fuel}$ (602 and 241 \$/ton$_{fuel}$), respectively. The difference between the first and future plant are substantial. These prices are distinguished in a baseline and advanced scenario.

Transport to airport
The fuel is delivered with a truck. The average cost price for transport is 1.64 €/km (NEM, 2009). The costs for transport with a typical fuel trailer are 5.82 €/ton$_{fuel}$.

Production costs biofuel
The prices are determined for four scenarios: two algae yields and a baseline and advanced scenario. The baseline scenario represents the first conversion HTU/HDO facility. The advanced scenario represents an advanced conversion facility, which results in lower production costs. A distinction is made between two algae yields of 12 and 30 DAFMT/ha/yr. The costs are summed up (in $2009/ton) in a cumulative column chart in Figure 46. The price of bio jet fuel is ranging from 770-1647 $/ton. A reference price of $700 per ton fossil fuel is given. If the fossil fuel price is in the range of 770-1647 $/ton, the bio jet fuel becomes economically competitive.

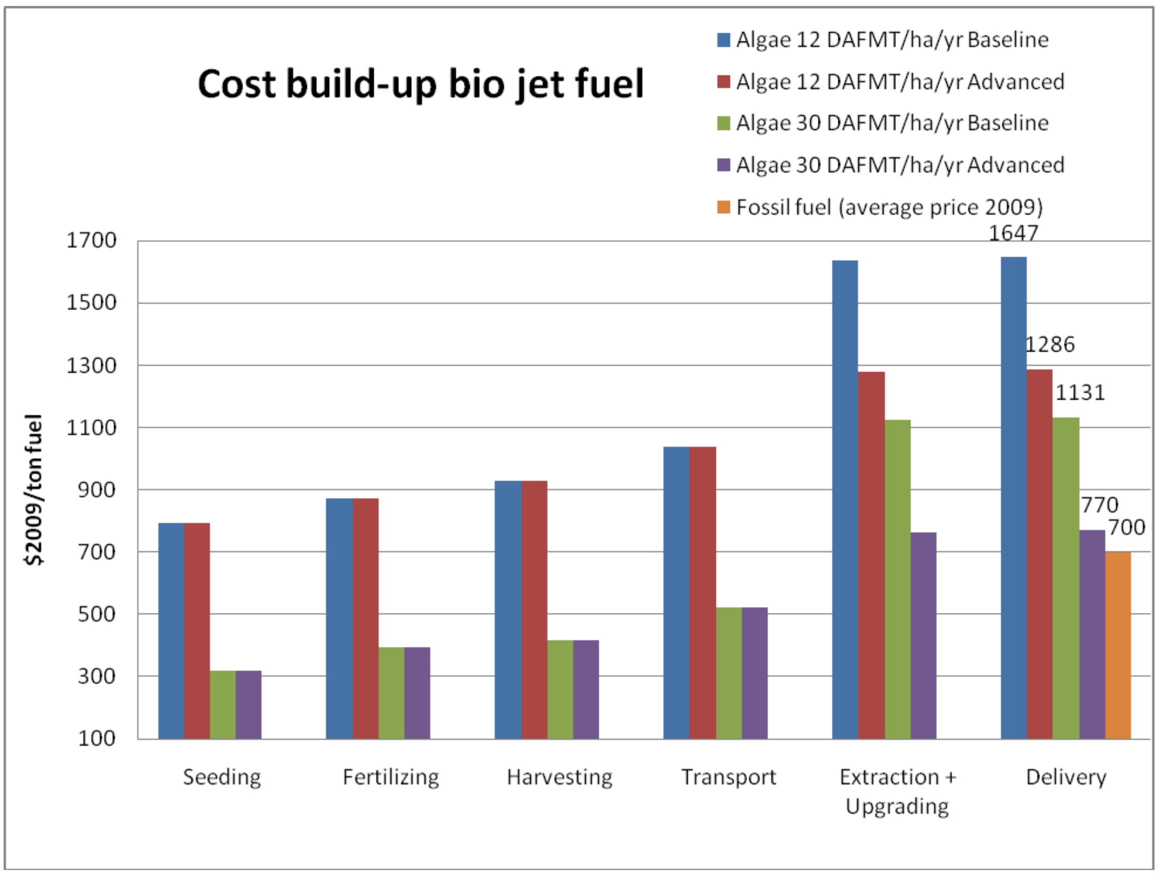

Figure 46 Cumulative cost price of bio jet fuel of four scenarios. The blue and red columns have a yield of 12 DAFMT/ha/yr. The purple and green lines have a higher yield of 30 DAFMT/ha/yr. The red and purple columns have a more advanced (cheaper) conversion.

In several papers it is calculated how much it will cost to cultivate macro algae. These are the combined costs of seeding, fertilizing, harvesting and transport. These are compared in Table 11. The outer right column ($\$2009/ton_{fuel}$) means the feedstock cost price for a ton fuel. Bird (1987) calculated the lowest cost of all, although these are slightly below the costs calculated in this report. Florentinus (2008) calculated a higher cost price.

Table 11 Macro algae production costs from several sources. Florentinus (2008) estimates a higher price than Bird (1987),

Source	$\$2009/ton_{daf}$	$€2009/ton_{daf}$	$\$2009/ton_{fuel}$
Figure 46			521-1037
Bird (1987)	53-138.7		185-485
Florentinus (2008)		220-600[1]	1077-2937

[1] $€/ton_{dry\ mass} \rightarrow 0.74\ ton_{daf}/ton_{dry\ mass}$

If the cost estimations of Florentinus (2008) prove to be true, the price of bio jet fuel is substantially larger. When cost estimations of Bird (1987) and from Figure 46 prove to be true, macro algae fuel will have a price in the range of fossil fuel. Reith (2008) described four points which influence the cost price of algae. Two factors are added that will determine the price of bio jet fuel. These five points are:

- Productivity of algae.
- Cost of cultivation system.
- Nutrient supply.
- Harvesting costs.
- Conversion costs.
- Demand.

These points are discussed with the results in Figure 46. The productivity does affect the seeding and harvesting price. Especially seeding costs are reduced significantly with increasing yields. This is in line with the second point from Reith (2008). Fertilizers are a small fraction of the total costs. It is assumed that these costs will be paid back in increased yields. The fourth point, harvesting costs, are in line with the calculations. Harvesting and transport to the conversion facility are less then 100 $€/ton_{fuel}$, a small fraction of the total costs. In these calculations, seeding and extraction + upgrading appear to be the two largest contributors to the price of algae fuel. Both approaches confirm that the cost-price of bio jet fuel declines if it is produced on a large scale. Before it can be mass-produced, it needs to be introduced. Experience will be gained that will bring down the costs, but the learning investment needs to be paid.

5.2.4 Acceleration in the transition of aviation fuel

As a result from the cost price determination of bio jet fuel in the previous two sections, the current cost-price of bio jet fuel would be 17.000 $2009/ton, see Figure 45. The price will go down substantially which is confirmed by both approaches when demand is increasing. In this section, several actions are discussed which will speed-up or slow-down the transition from fossil fuels to bio jet fuel. In Table 12, the actions are mentioned and will be discussed afterwards.

Table 12 Actions which will speed-up or slow-down the fuel transition

Speed-up	Slow-down
• Prohibit fossil fuels • Demand from defence • Consumers are willing to pay • Legislation promoting biofuels • Feed-in	• Competition between feedstocks • Strong growth is technically impossible

Prohibit fossil fuels
An effective action to accelerate the transition to biofuels is prohibiting fossil fuels. It is not a viable option apparently, the economy relies heavily on fossil fuels which will have an impact on the community. A gradual transition seems to be more viable.

Defence
Defence demands aviation fuel for their Air Force, especially the American which is looking for alternatives to become energy independent. The American air force consumes 7.7-9.6 million tons jet fuel per year and they are nation's largest single consumer of energy (Graham, 2009). Besides the Americans, European defence might be a potential customer, especially when energy security is a higher priority than energy price. They need large quantities of fuel and their investments bring down the production costs of bio jet fuel and this accelerates the transition.

Consumers
Consumers, the passengers who take the airplane are willing to pay for a flight which is powered by biofuel partly or fully. These passengers are aware of the affects of fossil fuels and they want to pay for a more environment friendly flight. Airlines can offer this, the question is how much the passenger will pay for it and what the percentage bio jet fuel should be. In the next action (legislation promoting biofuels), a case is worked-out how much the costs would be as a function of the price and percentage biofuel. Airlines can determine at what price they could offer a more environment friendly flight.

Legislation in promoting biofuels
Regulators can make legislation in promoting biofuels for example: tax incentives, mandates to use biofuel and in emissions standards. By doing so, a market is created in advantage for biofuels. The question is how much the cost will increase for airlines to fly with a blend of fossil fuel and bio jet fuel. A model is made to determine the increase in costs as a function of the price and percentage bio jet fuel.

The price of jet fuel which is a blend of fossil fuel and bio jet fuel is determined by:

y = Price jet A [$/ton]

a = Percentage bio jet fuel [%]

x = Price bio jet fuel [$/ton]

$$\text{Price jet fuel: } P_{jf} \text{ [\$/ton]} = a \cdot x + (1-a) \cdot y$$

The total costs and increase in costs can be determined for a specific flight. The average fuel consumption for aircraft is used and as a result, the average cost per seat is calculated. The total costs and increase in costs for a return trip are calculated by:

p = percentage fuel costs/total costs [%]

d = distance single trip [km]

c = average fuel consumption [kg/pax/100 km]

$$\text{Total fuel consumption: } T_{fc} \text{ [ton/pax]} = 2 \cdot 10^{-5} \cdot c \cdot d$$

$$\text{Cost return trip: } C_{rt} \text{ [\$/pax]} = T_{fc} \cdot P_{jf} + \left(\frac{1}{p} - 1\right) \cdot y \cdot T_{fc}$$

$$\text{Percentage increase in costs: } P_{ic} \text{ [\%]} = \frac{C_{rt} \cdot p}{y \cdot T_{fc}} - 1$$

The percentage increase in costs (P_{ic}) is independent of the distance of a flight.

This case is worked out for a return trip Amsterdam-New York City. The assumptions are:

$y = 700$ [$/ton]

$P = 25$ [%]

$c = 3.2$ [kg/pax/100km]

$d = 5870$ [km] Amsterdam - New York City

First, the price of jet fuel as a function of the price and the percentage of bio jet fuel is determined and plotted in Figure 47. From this, the costs for a return ticket per passenger as function of the price and percentage bio jet fuel can be calculated, see Figure 48. The costs without bio jet fuel and with 100% bio jet fuel at a bio jet fuel price of $17.000 would be $1.052 and $ 7.175, respectively, almost 7-fold. It is expected that demand will decline significantly with these prices. It is better to introduce bio jet fuel on a small scale, for example a blend containing 1% bio jet fuel. This is visualized in Figure 49, currently the cost-price would increase less than 6%. If passengers are willing to pay this premium, demand for bio jet fuel is created by the market itself. However, if there is a lack of demand, a mandate can be introduced. When demand for bio jet fuel grows, the price will decline and the blend with bio jet fuel can be increased. This loop continues until a full transition has been taken place.

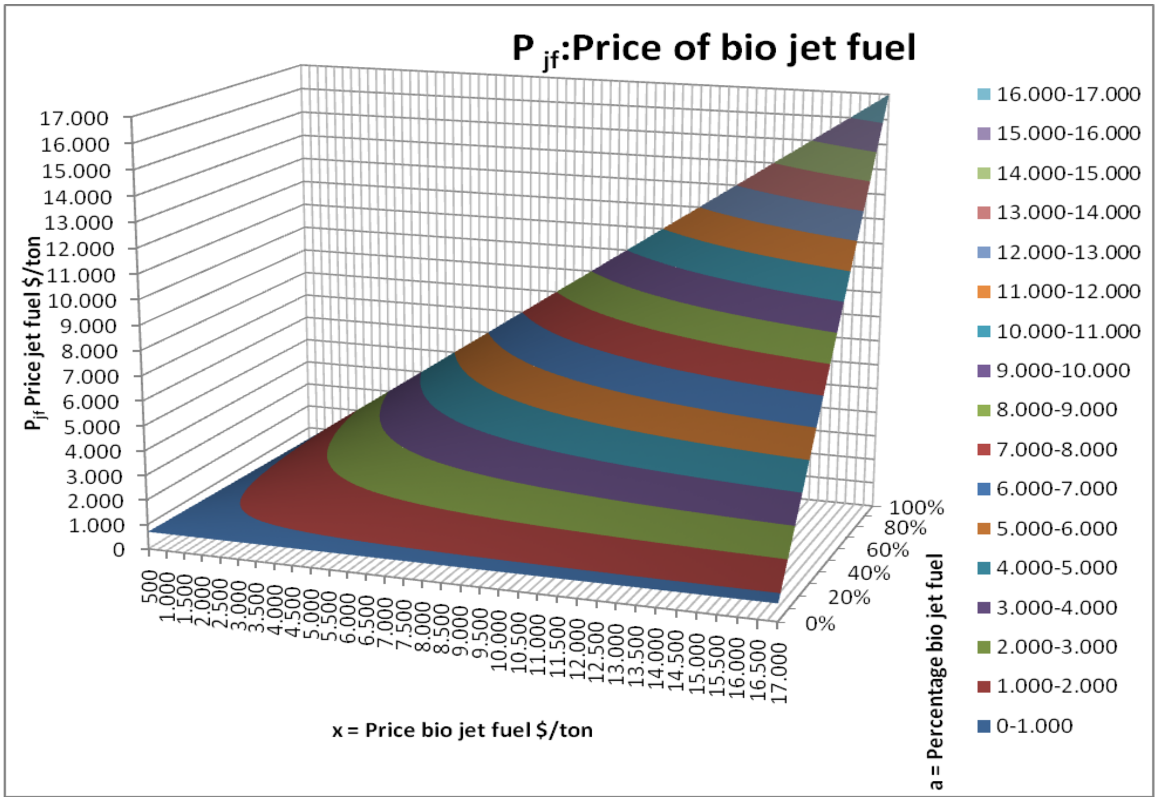

Figure 47 Price of jet fuel as a product of the percentage and the price of bio jet fuel.

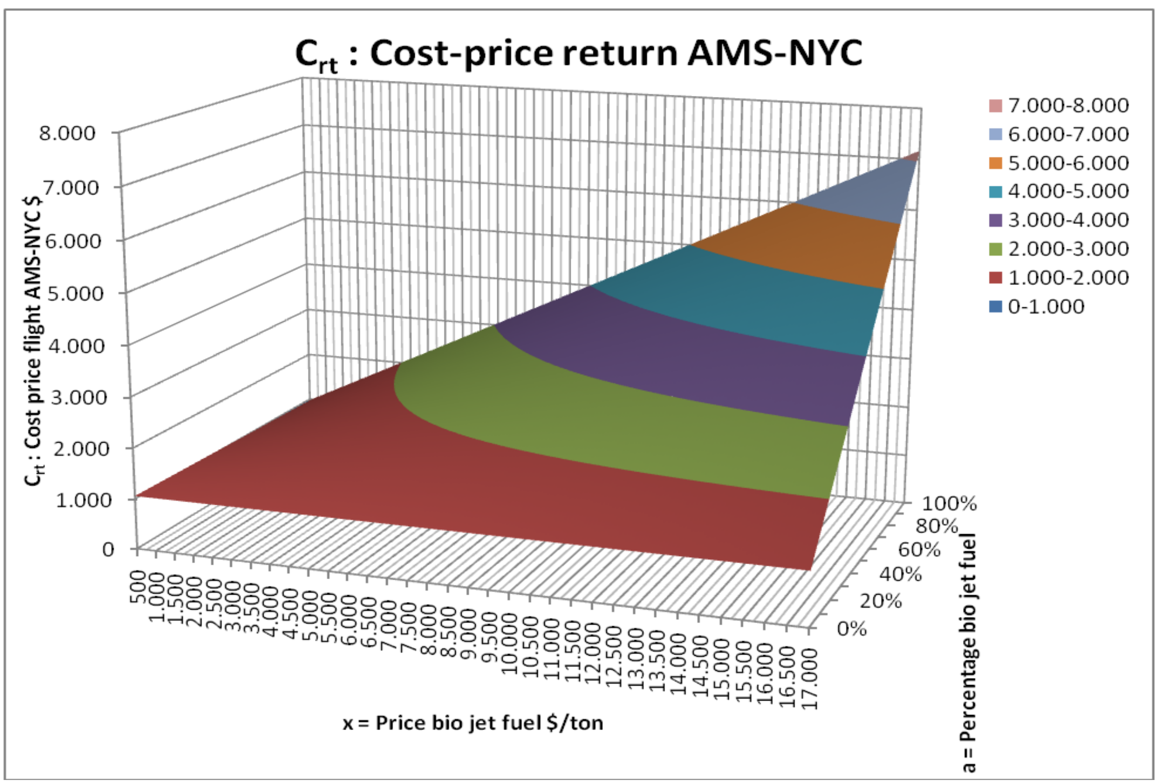

Figure 48 Cost-price return AMS-NYC as product of percentage and price of bio jet fuel. The cost-price for a return ticket with a bio jet fuel price of \$17.000/ton is \$7.175, almost 7-fold with a fossil fuel price of \$700/ton. It is advised to start with a blend with a small percentage bio jet fuel.

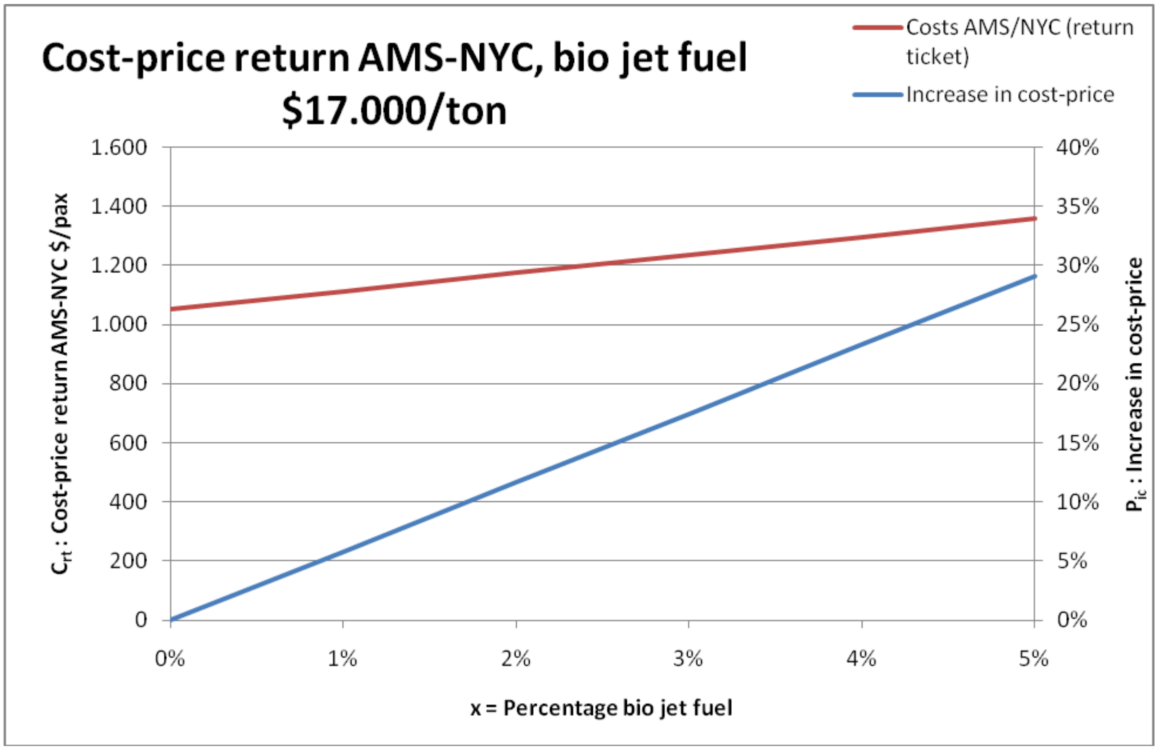

Figure 49 Cost-price return AMS-NYC for a bio jet fuel price of $17.000/ton. The cost-price of a return ticket will increase when the percentage bio jet fuel is increased. For a blend containing 1% bio jet fuel, the costs will increase by 6%.

Feed-in

Another option in legislation to accelerate the transition is the feed-in process. The unprofitable top (learning investment) is paid by a fuel surcharge. Airlines pay a fuel surcharge on top of the price of fossil fuel which is used to pay the learning investment pointed out in section 5.2.2. A global commitment between airlines, bio jet fuel producers and regulators is necessary for implementation. A plan is presented how this feed-in system will work for the transition to bio jet fuel.

The total investments per year is determined by the difference in price of fossil fuel and bio jet fuel times the total annual production:

$$\text{Investment } [\$] = \text{Weight Algae Fuel } [\text{ton}] \cdot \left(\text{Cost Fossil Fuel} \left[\$/_{\text{ton}} \right] \text{-Cost Algae Fuel} \left[\$/_{\text{ton}} \right] \right)$$

The profit is the summation of annual investments since start of the investments. Breakeven point has been reached when profit crosses the x-axis again.

$$\text{Profit}[\$] = \sum_{i}^{year} Investment[\$]$$

The investments are divided over the total aviation fuel consumption and this result in the fuel surcharge.

$$\text{Fuel Surcharge}\left[{}^{\$}\!/_{\text{ton}}\right] = -\frac{\text{Investment}[\$]}{\text{Total Aviation Fuel Consumption}[\text{ton}]}$$

The fuel surcharge is added to the fossil fuel costs. The expression only applies if the Fuel Surcharge is larger than zero.

$$\text{Fuel Costs}\left[{}^{\$}\!/_{\text{ton}}\right] = \text{Fossil Fuel}\left[{}^{\$}\!/_{\text{ton}}\right] + \text{Fuel Surcharge}\left[{}^{\$}\!/_{\text{ton}}\right]$$

If the Fuel Surcharge is smaller than zero:

$$\text{Fuel Costs}\left[{}^{\$}\!/_{\text{ton}}\right] = \text{Algae Fuel}\left[{}^{\$}\!/_{\text{ton}}\right]$$

The investment, profit, fuel surcharge, fuel costs are calculated and projected for the future. The assumptions in this model are:

- Production starts in 2015, first bio jet fuel is produced in 2016.
- Progression ratio of 0.59±0.013.
- Growth algae cultivation +25% annually, see Figure 50 for the energy mix.
- Growth annual demand fuel consumption +1.7%.
- Full transition from fossil fuel to bio jet fuel in 2047.
- Fossil fuel price follows light purple trend line assumed in Figure 41.
- All values are in $2009/ton.

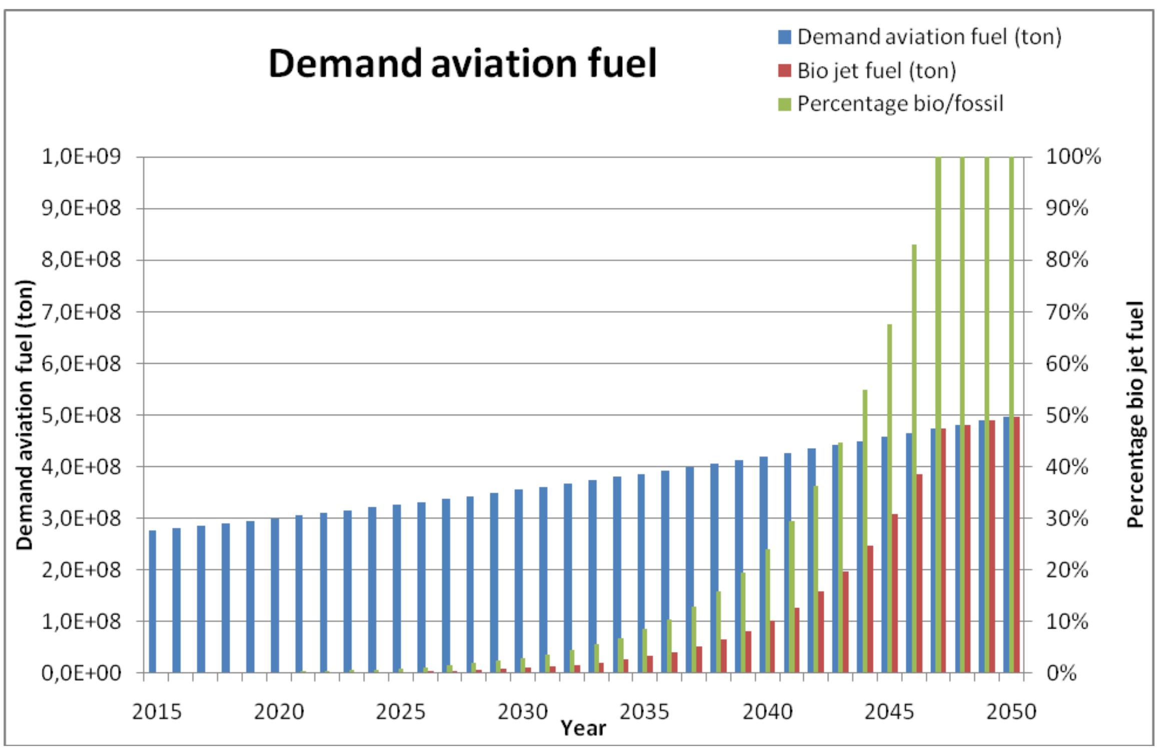

Figure 50 Demand aviation fuel by total demand and bio jet fuel demand.

Two graphs are plotted from this model. The investment/profit curve is plotted in Figure 51. The investments are given per year and summation of these results in the profit. The total investment is about $150 billion and the break-even point would be in 2040. However, the cost of capital and interest are not taken into account in the profit. The reason is that the investments are paid back in the same year by the additional fuel surcharge on the fossil fuel price.

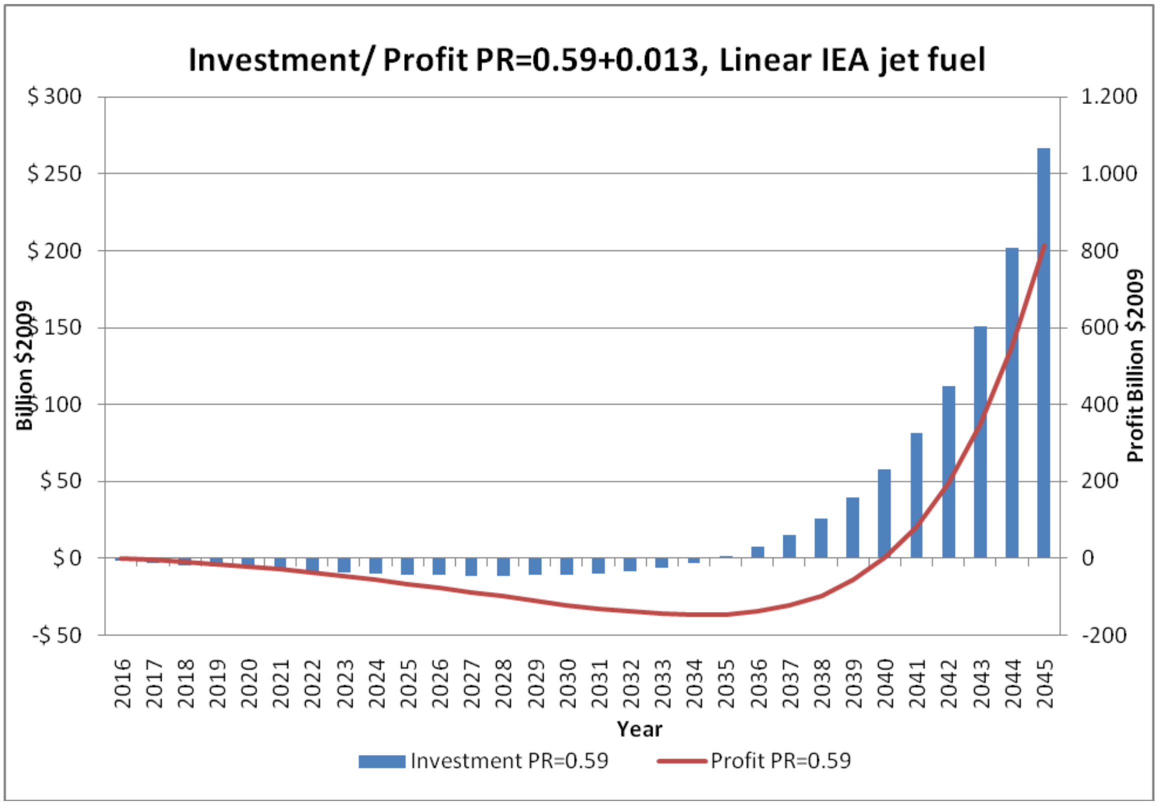

Figure 51 The investments for bio jet fuel annually. The profit is the summation of all investments. It will be profitable in 2045 whether no capital costs or interests are taken into account.

In Figure 41, the fossil fuel price has been forecasted by the IEA. It is assumed that the jet fuel price will follow the trend forecasted by the IEA. The trend line of the linear regression is used too. This will show what will happen with the fuel surcharge if the fossil fuel price appears to be lower. The red and green linear lines represent the forecasted fossil fuel price of the linear regression and IEA from Figure 41. The total fuel costs are the purple and orange line for the forecast of the linear regression and IEA. The total cost of fuel, which is the cost of fossil fuel and the fuel surcharge, is plotted in Figure 52. As a result from this model, the percentage fuel surcharge and crossing point are known. The percentage fuel surcharge is the percentage fuel surcharge of the total fuel costs and the crossing point is the year that bio jet fuel becomes cheaper than fossil fuel. These data is given in Table 13.

Table 13 Percentage fuel surcharge, crossing point and break-even point for two forecasts of the jet fuel price and for the progression ratio with both errors.

	Percentage fuel surcharge (%)	Crossing point
PR=0.59+0.013		
Linear history	7.1	2040
Linear IEA jet fuel	3.8	2035
PR=0.59-0.013		
Linear history	5.6	2038
Linear IEA jet fuel	3.2	2034

Figure 52 tells, the total price of the fuel is determined mainly (93%-100%) by the price of fossil fuel until the price of bio jet fuel is lower than fossil fuel. This will happen in 2034-2040. In 2035, only 10% of the blend is bio jet fuel. The price can go down further as can be seen in the figure if the progression ratio is sustained. In Figure 52, the price of fossil fuel and the total cost show very smooth lines. It is a theoretical approach and in reality, internal and external factors will influence the price of fossil fuel and bio jet fuel. As a result, the total price will fluctuate and these are determined mainly by the price of fossil fuel before the crossing point. The fuel surcharge is steady between 3-7% of the total price.

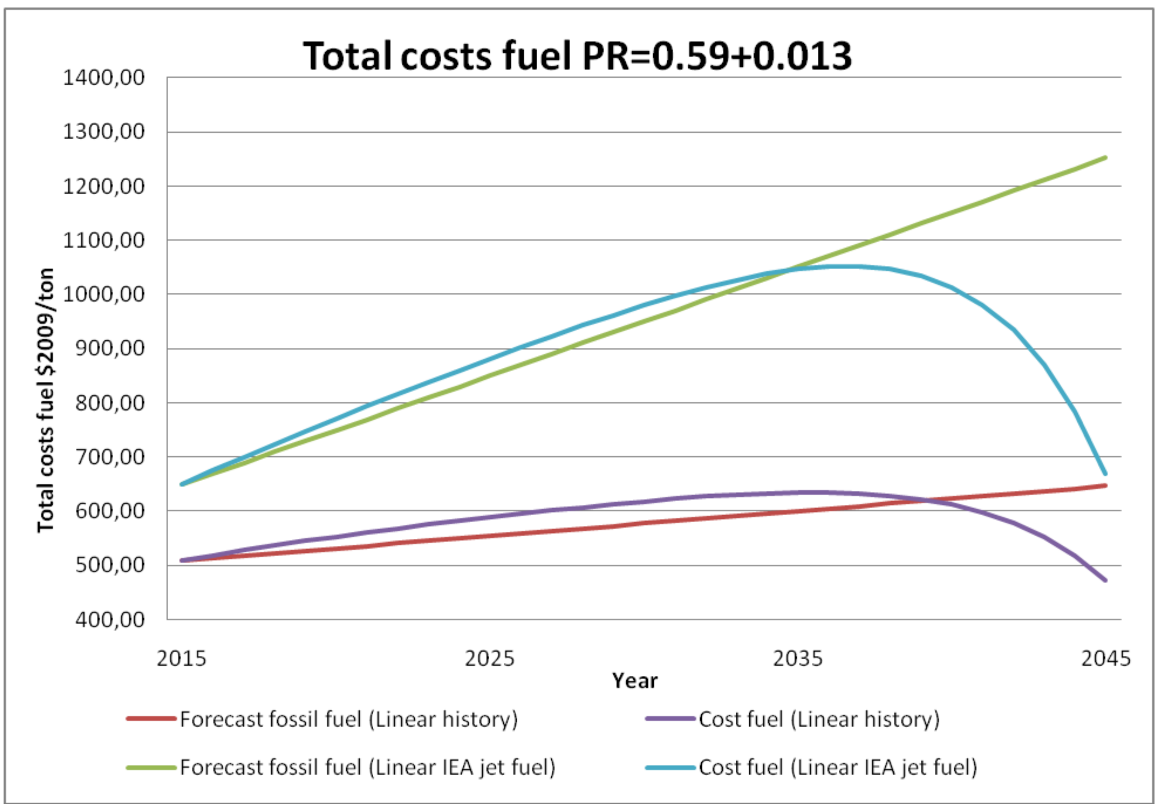

Figure 52 Projected fuel price 2016-2050. The linear lines represent the forecast of fossil fuel. The others represent the total costs of fuel. This is a blend of fossil fuel and bio jet fuel and the transition takes gradually place. In this model bio jet fuel becomes economically competitive in 2038-2041.

The question will be if the progression ratio is sustained over the whole period. A second model with a PR of 0.68±0.03 (reference of sugarcane) is presented in Appendix 8. Obviously, the investments, fuel surcharge and break-even point are higher due to the larger progression ratio. An essential element in the success of bio jet fuel from macro algae is sustaining the progression ratio.

In Table 12, two items are mentioned which will slow-down the transition to bio jet fuel. These items are discussed briefly.

Competition between feedstocks
Macro algae are not the only feedstock for bio jet fuel. For example, other possible feedstocks are: camelina, jatropha, micro algae etc. When it turns out that the production costs of these feedstocks are cheaper, also on large scale without compromising the needs of future generations, it could be a thread to macro algae.

Strong growth is technically impossible
The transition should take place in a time frame of roughly 30-years. The growth in this time-frame is substantially which is 25% per annum. It could be that the strong growth in production and conversion is impossible and it slows-down the transition.

6 Conclusion

Aviation is continuously working towards reduced fuel consumption, greener and a more sustainable industry. Several projects into biofuels for aviation are running. The idea originated from the background information to produce aviation fuel from macro algae as alternative jet fuel. This was a feasibility study into the end-to-end chain of macro algae to bio jet fuel. It is feasible whether the four requirements are fulfilled which were defined in this research. These are discussed.

Macro algae have been cultivated for decades, mainly for food production in South East Asia. Four cultivation methods are described by Bird (1987) and the most promising are floating or attached macro algae cultivation near shore. Yields are ranging from 12-30 DAFMT/ha/yr, which result with the HTU/HDO process in a bio jet fuel yield of 3.4-8.6 ton/ha/yr. These yields are sustained if these three elements are sufficiently available: nutrients, light and carbon. Nutrients are usually the limiting factor in the growth phase of macro algae (Bird 1987, Gao 1992). Two main nutrients are nitrogen and phosphate and the supplies are not sustainable currently. Natural gas is used to produce nitrogen fertilizer and phosphate is mined in phosphate rocks. It is advised to cultivate these macro algae in nutrient rich waters. This is in favour of the energy balance and carbon dioxide balance. Additionally, the nutrients can be extracted from the conversion process and returned into fertilizer useful in agriculture. As a result, a renewable production of macro algae is created. The location to cultivate macro algae should be judged on sustainability criteria. The cultivation of macro algae should not deplete natural resources or destroy eco-systems.

The energy balance is defined as the energy returned on energy invested (EROEI). Macro algae fuel has an EROEI in the range 4.5-5.1 which is required for feasibility. Fertilizer is included, which affects the EROEI negatively. The EROEI is substantially larger than other biofuels except for sugarcane ethanol. Biofuel based on corn (ethanol), rapeseed (biodiesel) and sugarcane (ethanol) have EROEIs of 0.4, 1.5 and 7, respectively. Fossil fuel has an EROEI of 6.6. The carbon dioxide emissions from fossil fuel in the end-to-end chain are 3.5 kg CO_2/kg_{fuel}. Emissions from biofuel are different, because the carbon is absorbed by biomass in its growth phase and later on emitted when the fuel is burned. Energy is supplied externally during production, which also produces carbon dioxide. The emissions are 0.9 kg CO_2/kg bio jet fuel, a reduction of 75%. However, there is an uncertainty in the life-time of carbon dioxide in the atmosphere. Currently, about 50% of the emissions are absorbed by the oceans. It is uncertain if all carbon that is absorbed by the algae, is supplied from atmospheric carbon dioxide. If the absorption is 50% at maximum, the total emissions are still less than fossil fuels, but the difference is marginal. In the HTU/HDO processes, also CO_2 is produced and these may be captured and stored in the future, but currently it is uncertain if this is technologically possible.

A hybrid approach was used to determine the production costs of bio jet fuel from macro algae. Experience curves are used to predict future production costs. These cannot be used to forecast price development of algal aviation fuel. Price depends on demand and supply in the end-to-end chain. The crop macro algae have a progression ratio (PR) of 0.59±0.013. This PR was further used in combination with other assumptions to forecast the production costs of algae bio jet fuel. Currently, algae fuel is much more expensive than fossil fuels. Costs will decrease thanks to the progression ratio of macro algae. In the second approach, a bottom-up calculation is used to determine production costs. Production costs are determined for four different scenarios. The cost of each process is summed up for each scenario. The four scenarios show production costs of algal fuel in the range 770-1647 $/ton. This price range is also in line with the first approach. It can be concluded from the hybrid approach that the cost-price of algae fuel will be in this range when the fuel is mass-produced.

Several actions can be taken to accelerate the demand in bio jet fuel. For example, defence can buy bio jet fuel to secure their energy supply. Airlines can provide flights powered by bio jet fuel partly or fully, because there is demand from the market. Another action could be legislation to promote biofuels, options are a mandate to add a percentage of biofuel or a feed-in system. If a blend with 1% bio jet fuel is used, which is introduced by a mandate or the airline itself the total costs for an airline will increase with 6%. The feed-in system is a long-term plan to pay the investments. These investments are paid by a fuel surcharge on top of the jet fuel price. The maximum fuel surcharge is 3-7% of the fossil fuel price for a progression ratio of 0.59±0.013. With legislation in promoting biofuels, a global collaboration between bio jet fuel producers, airlines and authorities are necessary.

Discussion of results

Feasibility was defined in section 2 as:

- Renewable and sustainable production of all demanded aviation fuel. ☑
- A positive energy balance in the end-to-end chain (EROEI>4). ☑
- Reduced carbon dioxide emissions in the end-to-end chain (>75%). ☑**?**
- Economical viability. ☑

It can be concluded that it is feasible to produce macro algae fuel in a sustainable and economical manner. There is an uncertainty in the life-time of carbon dioxide in the atmosphere. If all absorbed carbon by the macro algae are supplied from the atmosphere, the target is met. The economical viability is determined by the demand which can be created by defence, consumers (passengers) or by legislation. Essential items in the transition to bio jet fuels are:

- Global collaboration of industry and regulators in the transition to bio jet fuel.
- Long term legislation with concrete annual targets and goals
- Collaboration in the end-to-end chain to avoid unbalanced demand and supply which affects prices negatively.
- Monitor progression

Recommendations

- Set-up business plan and find funding for a small pilot plant to cultivate macro algae.
- Further research to nutrient cycle, how to use nutrients as efficient as possible and how to extract the nutrients again during the conversion process.
- Produce bio jet fuel, test it on specifications and make tests-flights.
- Convince airlines and authorities about the urgency of transition to biofuels. Make legislation for the long term with concrete goals and targets, and control them as well.

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Appendix 1: End-to-end chain fossil fuel

Aviation fuel is produced in several processes. An overview of the end-to-end chain is of importance to get insight where the aviation fuel comes from and how it is produced. The supply chain visualizes the necessary steps. In essence, three processes are necessary from well to wing. These are oil recovery upstream and oil refining and distribution downstream, see Figure 53. Every process is further outlined.

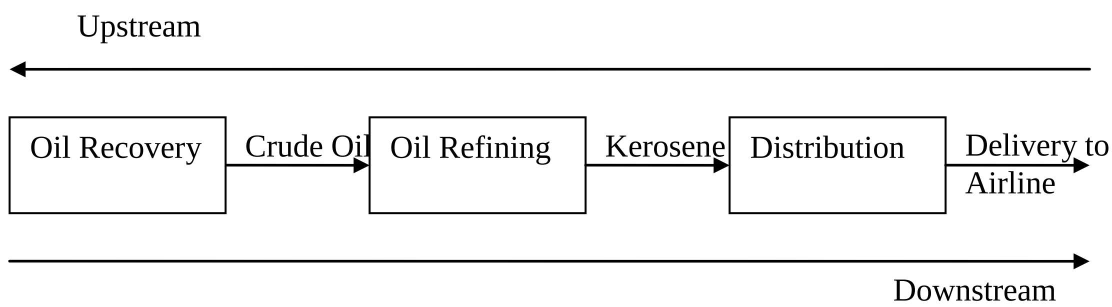


Figure 53 Supply Chain Aviation Fuel. The three major processes are oil recovery, oil refining and distribution.

Oil recovery

Crude oil is a natural multi-component mixture. The major part is composed of hydrocarbons: alkenes, naphthenes and aromatics. Other components are resins, asphaltenes and metals. The earth is about five billion years old and forming crude oil started about three billion years ago. All discovered oil and gas accumulations point clearly to organic origins. Sapropelic is a marine sediment at the sea bottom rich in organic material, mainly algae in the absence of oxygen. It was believed that sapropelic played a major role in oil generation (Chilingar, 2005). This means that crude oil is mainly formed from algae. "Oil shale was formed by the deposition and lithifaction of finely divided mineral matter and organic debris in the bottom of shallow lake and seas. The organic debris resulted from the mechanical and chemical degradation of small aquatic algal organism" (Yen, 1976).

Wells are drilled for exploitation and recovery. The major part is recovered by state owned oil companies. The rest is recovered by private companies and are usually more energy intensive to mine. Crude oil is sold to the world market for refining.

Oil refining

The crude oil is transported via a network of pipelines and bulk carriers to refineries. The oil is distilled to different fractions of fuel. The fraction kerosene or Jet A-1 is in the range C_{11-16}. Heavier fractions can be cracked where smaller fractions are formed. The bonds between the carbon molecules are cracked and hydrogen is supplied to form smaller carbohydrate chains. Other treatments can be done as well. An example is the removal of contaminants such as sulphur and nitrogen.

Distribution
Jet A-1 is ready for use and must be transported to airports. Nearly all aircraft movements depart from and arrive at main ports. Distribution is relatively centralized compared to gas stations. Fuel is transported easily from refineries to airports via pipelines or other forms of bulk transport. The end user is the airline.

Energy balance Jet A-1

The easiest way to calculate the well-to-tank efficiency is to define a supply chain and calculate the used energy until the tank. In the end, the efficiency is compared with numbers from the literature.

In this example, crude oil is recovered in the Middle East. The oil is easily recoverable; no energy is needed for recovery. The oil flows out of the well, because of the earth surface pressure. Transport to the harbour is ignored. The crude oil is loaded on a bulk carrier vessel and transported to Rotterdam over a distance of 7400 km (4000 NM). The crude oil is refined in Rotterdam and transported to Schiphol Airport in Amsterdam via road transport over a distance of 100 km. In reality, Jet A-1 is transported in pipelines to Schiphol.

Energy use sea transport
The crude oil is transported with a bulk vessel "Dubai Star" (Significant Ships of 2007, 2007). This vessel is capable of transporting 44.242 tons of crude oil. The fuel consumption is 31.89 ton/day at a speed of 27.6 km/h (14.9 knots). The distance Jeddah-Rotterdam is 7400 km, but we must take the return trip into account. Probably these vessels sail back empty. The total transport distance is 14.800 km. The total fuel consumption will be 714 tons. The efficiency is 98.4%.

Energy use oil refining
Several oil refineries are located in the harbour of Rotterdam. The Dutch Bureau of Statistics (CBS) tracks the statistics of crude oil and oil products in the Netherlands (source www.cbs.nl). In 2008, 52.64 PJ (1.25 million tons of fuel) was used for refining and 1222.6 PJ (29.10 million tons of fuel) was produced. The refining efficiency is 95.9%. Van Vliet (2009) states a refinery consumes 0.1 $MJ/MJ_{produced\ diesel}$, which means refining efficiency is 90%.

Energy use road transport
The last step is to deliver fuel at the airport. The fuel is transported from the refinery in Rotterdam to Schiphol Airport in Amsterdam. The distance is 100 km and we must take into account the return trip as well for the same reason as in the vessel's case. Road transport happens with a truck and fuel trailer. Such equipment is capable of carrying 35.000 litres of fuel and the truck has a typical fuel consumption of 1 litre per 3 kilometres. The fuel consumption will be 67 litres. The efficiency is 99.8%.

Well-to-tank efficiency

The efficiencies in the processes are calculated. Multiplication yields the total well-to-tank efficiency, which is equal to 94%. This number sounds too optimistic, because two references show an efficiency slightly less than 94%. According to Van Vliet (2009), the well-to-wheel efficiency is 91%. Landolt-Bornstein (2002) states the total well-to-tank efficiency is less, respectively 88.4%. In those calculations, energy use for oil recovery is taken into account, which is 99%. Sea transport and refinery are similar, respectively 98% and 94%. The major difference is distribution and delivery, 96%. An answer could be the decentralization of gas filling stations that results in less efficient road transport.

CO_2 emissions

The total carbon dioxide emissions that are produced in the supply chain must be calculated. The energy use in oil recovery and transport to harbour are assumed to be negligible. Emissions are for sea transport, oil refinery, distribution and finally when the Jet A-1 is burned to propel aircraft. An oil refinery emits 0.370 kg CO_2/ kg produced fuel, Van Vliet (2009). The fuel usages for (sea) transport are known from the previous section. The CO_2 emissions from a kilogram fuel are calculated with the stoichiometric equation.

$$C_xH_{2x+2}+\left(\frac{3}{2}x+\frac{1}{2}\right)O_2 \rightarrow xCO_2+\left(x+1\right)H_2O$$

The atomic masses are:
C=12
H=1
O=16

Jet A-1 fuel is usually in the range $C_{12\text{-}16}$. The carbon dioxide emissions are calculated with x=15. A kilogram fuel emits:

$$\frac{12x+2\cdot16x}{12x+2x+2}\frac{kgCO_2}{kgFuel}=3.1\frac{kgCO_2}{kgFuel}$$

The carbon dioxide emissions are specified in Table 14 in kg CO_2 per kg fuel. In the end-to-end chain, one kg fuel emits 3.5 kg CO_2.

Table 14 CO_2 emissions per unit fuel

	kg CO_2/kg fuel
Oil recovery	0
Sea transport	0.025
Refinery	0.370
Delivery	0.006
Fuel burn	3.1
Total CO_2 emissions	3.5

Appendix 2: Weight analysis macro algae species Laminaria

Macro algae species: Laminaria

Proximate analysis		kg/kg wet	kg/kg dry mass	kg/kg daf
Moisture		0.88	8.33	11.26
Dry mass		0.12	1.00	1.35
Ash		0.03	0.26	0.35
DAF		0.09	0.74	1.00
Ultimate analysis				
C		0.0415	0.3460	0.4676
H		0.0056	0.0470	0.0635
O		0.0374	0.3120	0.4216
N		0.0029	0.0240	0.0324
S		0.0012	0.0100	0.0135
P		0.0004	0.0035	0.0048
Total				
LHV	MJ/kg	1.5	12.2	16.5
HHV	MJ/kg	1.6	13.2	17.8

Appendix 3: Yields from HTU/HDO conversion process

Yields from an input of 1 DAFMT.

Laminaria		C	H	O	Nutrients	Ton			
		0.468	0.064	0.422	0.051	1			
H_20	20%	0.000	0.022	0.178	0.000	0.200			
CO_2	23%	0.063	0.000	0.167	0.000	0.230			
CO	2%	0.009	0.000	0.011	0.000	0.020			
Organics	10%	0.050	0.000	0.000	0.051	0.101			
Biocrude	45%	0.346	0.041	0.065	0.000	0.453	Output		
							Kerosene	0.200	ton fuel/ton DAF
Light biocrude	70%	0.242	0.029	0.046	0.000	0.317	Kerosene	5.007	ton DAF/ton fuel
Heavy biocrude	30%	0.104	0.012	0.020	0.000	0.136	Naphtha	0.086	ton naphtha/ton DAF
							Naphtha	11.683	ton DAF/ton naphtha
Gasification	CO	0.104		0.139		0.242	CO_2	0.826	ton CO_2/ton DAF
	H_2		0.012			0.012	CO_2	2.894	ton CO_2/ton fuel
WGS	CO_2	0.112		0.300		0.412			
	H_2		0.019			0.019			
HDO	Kerosene	0.170	0.030			0.200			
	Naphtha	0.073	0.013			0.086			
	H_20		0.005	0.046		0.051			

Appendix 4: Global potassium reserves

Global phosphate production from phosphate rocks is given in Table 15 (Jasinski, 2009). Phosphate reserves in phosphate rocks are given as well. A distinction is made between reserve and reserve base. Reserve are proven phosphate sediments and economical minable. Reserve base are proven and not economical recoverable. The reserves are given in a pie chart too, see Figure 54. China, Morocco and the Western Sahara contain two third of the phosphate rock reserves.

Table 15: Global phosphate reserves (Jasinski, 2009).

x1000 Ton	Mine Production			
	2007	2008	Reserve	Reserve Base
United States	29,700	30,900	1,200,000	3,400,000
Australia	2,200	2,300	82,000	1,200,000
Brazil	6,000	6,000	260,000	1,200,000
Canada	700	800	25,000	200,000
China	45,400	50,000	4,100,000	10,000,000
Egypt	2,200	3,000	100,000	760,000
Israel	3,100	3,100	180,000	800,000
Jordan	5,540	5,500	900,000	1,700,000
Morocco and Western Sahara	27,000	28,000	5,700,000	21,000,000
Russia	11,000	11,000	200,000	1,000,000
Senegal	600	600	50,000	160,000
South Africa	2,560	2,400	1,500,000	2,500,000
Syria	3,700	3,700	100,000	800,000
Togo	800	800	30,000	600,000
Tunisia	7,800	7,800	100,000	600,000
Other countries	8,110	10,800	890,000	2,200,000
World total (rounded)	156,410	166,700	15,417,000	48,120,000

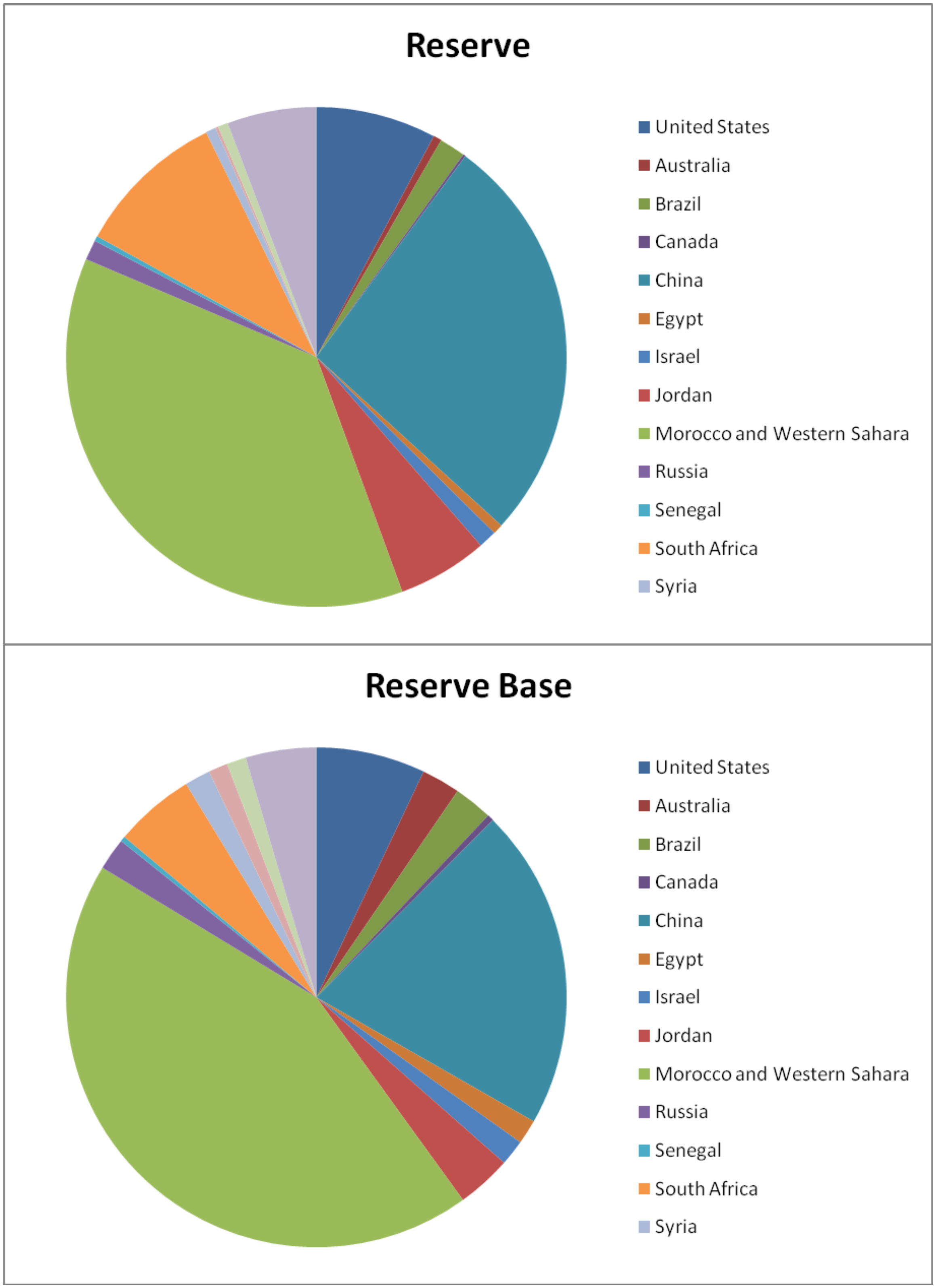


Figure 54 Global phosphate reserves by country (Jasinski, 2009).

Appendix 5: Annual mean solar irradiance

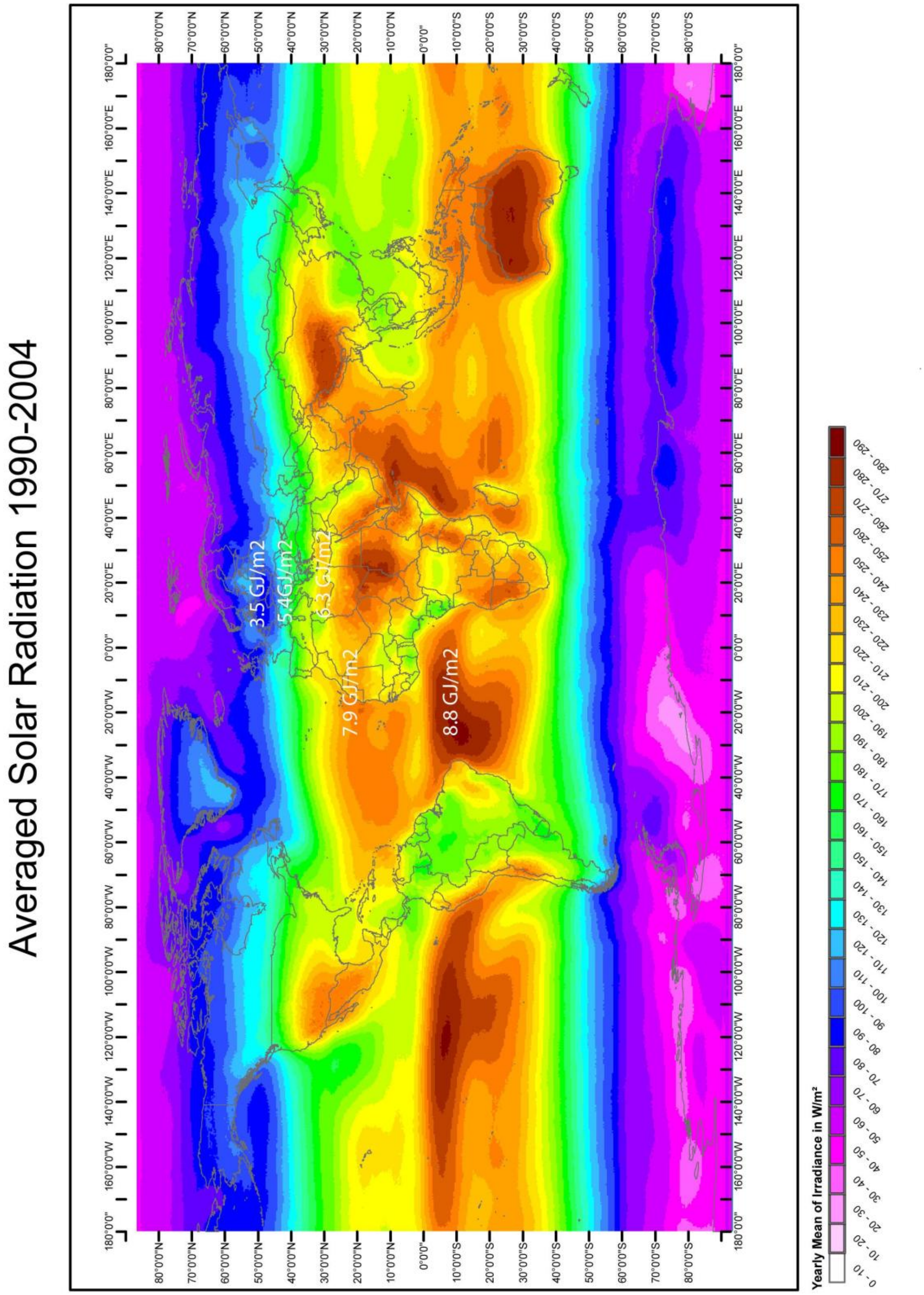


Figure 55 World yearly mean solar irradiance (source: Ecole des Mines de Paris / Armines 2006).

Appendix 6: Specifications of harvester and transport from cultivation to conversion

Table 16 Harvesting specifications.

Algae			
Yield	12	30	DAFMT/ha/yr
LHV	20.3	20.3	MJ/kg DAF
DAF/wet wt	7.8%	7.8%	
yield/ha	4.9	12.2	Ton fuel/ha/yr
Harvesting			
Operational	300	300	days/yr
Daily			
Ship	24	10	ships
Storage capacity	4500	4500	m^3
Weight	13500	13500	ton
Width harvesting	10	10	m
Velocity harvesting	2.5	2.5	m/s
Engine	3000	3000	kW
Fuel consumptions	180	180	g/kWh
Fuel consumption harvesting	540	540	kg/hr
Area			
Ship	20000	20000	ha/ship/yr
Production	240,000	600,000	DAFMT/yr/ship
Production/day	800	2000	DAFMT/day/ship
Area/day	66.67	66.67	ha/day/ship
Harvesting hrs/day	7.41	7.41	hrs/day/ship
Total operation/day	7.41	7.41	hrs/day/ship
Wet wt/day	10256	25641	wet tons/day
Fuel consumption	4,000	4,000	kg/day/ship
Emitted CO_2	14,004	14,004	kg
CO_2 production	0.043	0.017	$kgCO_2/kg_{fuel}$
Energy use	0.012	0.005	MJ/MJ_{fuel}

Table 17 Data transport algal biomass by barges

Transport			
Yield	12	30	DAFMT/ha/yr
Capacity barge	2000	2000	Ton
number barges	10	26	
Transport per shipment	324.00	810.00	Ton fuel/day
Tug			
Transport velocity	7.5	7.5	m/s
Travel time 200 km	7.41	7.41	hr
Fuel consumption	0.0045	0.0045	kg fuel/ ton km
Fuel consumption	9173	22934	kg/day
Emitted CO_2	32,116	80,290	kg CO_2
CO_2 production	0.10	0.10	$kgCO_2/kg_{fuel}$
Energy use	0.028	0.028	MJ/MJ_{fuel}

Appendix 7: Carbon dioxide emissions

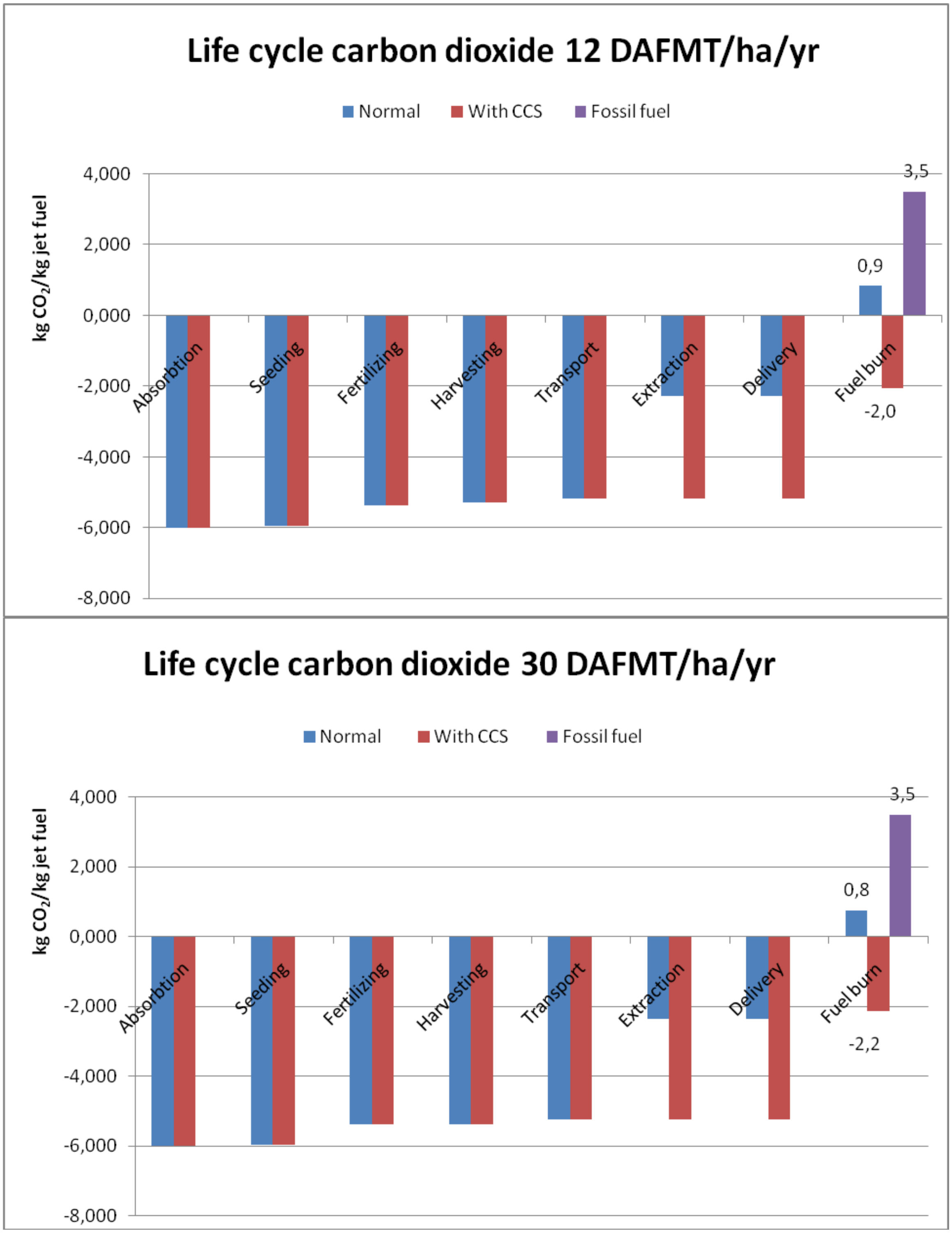


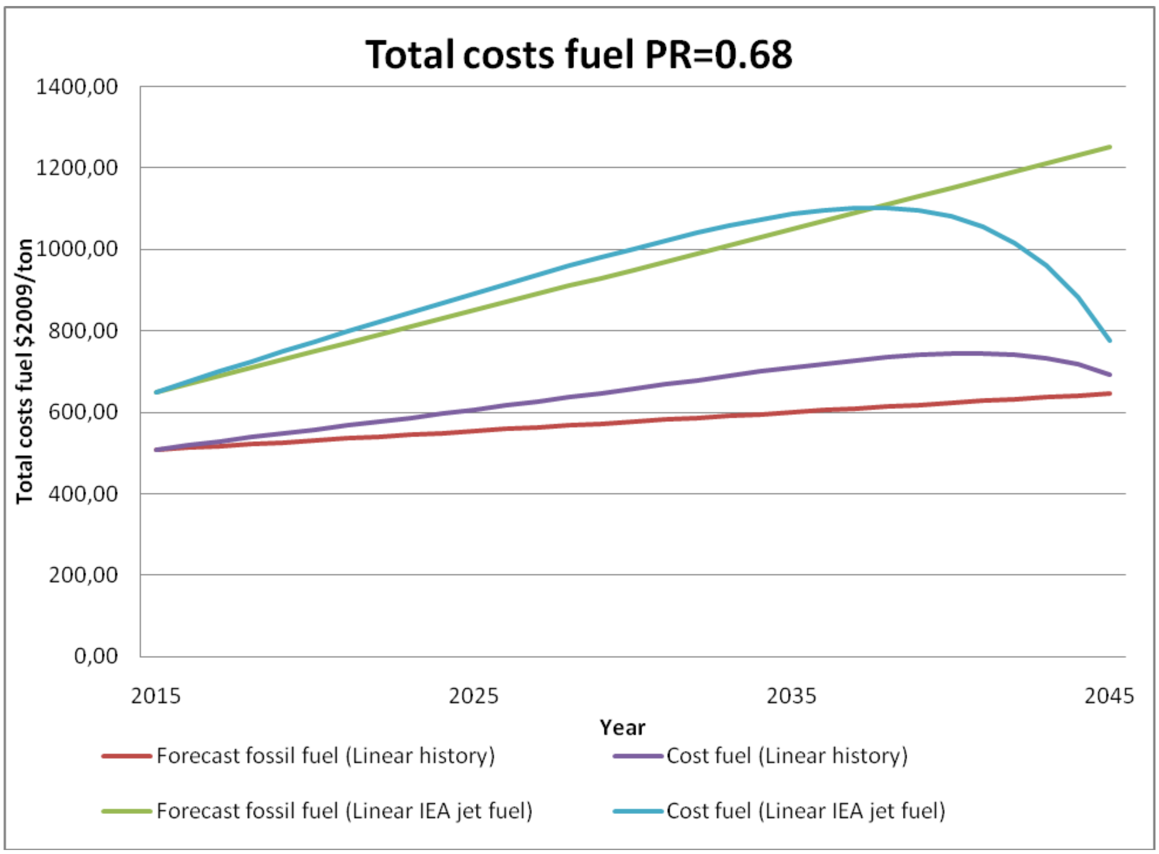
Figure 56 Carbon dioxide emissions in several scenarios.

Appendix 8: Cost price of bio jet fuel with a PR=0.68

This is a second model in addition of section 5.2.2. The cost price of macro algae were forecasted with a progression ratio of 0.59±0.013. This model will show what happens if the progression ratio is not sustained, but will be 0.68±0.03. In this case, the x-axis represents time and the y-axis represents fuel cost in $\$2008/ton_{fuel}$. In this scenario is assumed:

- Production starts in 2015
- PR: 0.68±0.03 (Sugarcane)
- Fuel yield: 0.025 $ton_{fuel}/ton_{wet\ algae}$
- Growth algae production: +25% annually
- Growth annual demand fuel consumption +1.7%
- Fossil fuel price follows light purple trend line assumed in Figure 41.
- Conversion price start with 602 $\$/ton_{fuel}$ and rapidly decreases to 241 $\$/ton_{fuel}$.

The red and green linear lines represent the forecasted fossil fuel price of the linear regression and IEA from Figure 41. The total fuel costs are the purple and orange line for the forecast of the linear regression and IEA. The total cost of fuel, which is the cost of fossil fuel and the fuel surcharge, is plotted in Figure 52. For the jet fuel price forecasted by the IEA, the percentage fuel surcharge and crossing point are 7.5% and 2040. For the linear regression line 20% and 2047.



Appendix 9: Economics

Yield:12 DAFMT/ha/yr.

Seeding						
Capital	9,710	€/ha			284	€/ton fuel
Cost of capital	10%				284	€/ton fuel
				Total	567	€/ton fuel
Fertilizing						
Fertilizer	432.5	€/ton fertilizer				
N Fertilizer	0.109	ton N/ton fuel			47	€/ton fuel
P Fertilizer	0.019	ton P/ton fuel			8	€/ton fuel
		Total			55	€/ton fuel
Harvesting	228	ton fuel/day				
Harvester	5,000,000	Depreciation 10 yr			7	€/ton fuel
Cost of capital	10%				7	€/ton fuel
Maintenance	1%	of harvester			1	€/ton fuel
Labour 2crew	6	50,000		300,000	4	€/ton fuel
Fuel	5,000				21.9	€/ton fuel
				Total	42	€/ton fuel
Transport	228	ton fuel/day				
Tug	1,000,000	Depreciation 10 yr			1	€/ton fuel
Barge	9,000,000	Depreciation 10 yr			13	€/ton fuel
Cost of capital	10%				15	€/ton fuel
Maintenance	1%				1	€/ton fuel
Crew	2		50,000	100,000	1	€/ton fuel
Fuel	10,072	kg			44	€/ton fuel
				Total	76	€/ton fuel
Extraction and upgrading						
LHV bio jet fuel	43	GJ/ton jet fuel				
First plant	10	€/GJ			430	€/ton fuel
Delivery						
Cost price	1.64	€/km				
Distance	100	km				
Fuel capacity	28	ton				
				Total	6	€/ton fuel

Yield: 30 DAFMT/ha/yr.

seeding						
Capital	9,710	€/ha			113	€/ton fuel
Cost of capital	10%				113	€/ton fuel
			Total		227	€/ton fuel
Fertilizing						
Fertilizer	432.5	€/ton fertilizer				
N Fertilizer	0.109	ton N/ton fuel			47	€/ton fuel
P Fertilizer	0.019	ton P/ton fuel			8	€/ton fuel
			Total		55	€/ton fuel
Harvesting	571	ton fuel/day				
Harvester	5,000,000	Depreciation 10 yr			3	€/ton fuel
Cost of capital	10%				3	€/ton fuel
Maintenance	1%	of harvester			0.3	€/ton fuel
Labour 2crew	6	50,000		300,000	2	€/ton fuel
Fuel	5,000	kg			9	€/ton fuel
			Total		17	€/ton fuel
Transport	571	ton fuel/day				
Tug	1,000,000	Depreciation 10 yr			1	€/ton fuel
Barge	22,500,000	Depreciation 10 yr			13	€/ton fuel
Cost of capital	10%				14	€/ton fuel
Maintenance	1%				1	€/ton fuel
Crew	2	50000		100000	1	€/ton fuel
Fuel	25,180	kg			44	€/ton fuel
			Total		74	€/ton
Extraction and upgrading						
LHV bio jet fuel	43	GJ/ton				
Future plant	4	€/GJ	Total		172	€/ton fuel
Delivery						
Cost price	1.64	€/km				
Distance	100	km				
Fuel capacity	28	ton				
			Total		6	€/ton fuel

Appendix 10: Limitations of the experience curve Junginger (2008)

A number of methodological limitations have been described by Junginger (2008). Below, the list of limitation has been copied:

- Experience curve theory appears not to include the effects of increasing raw material costs, at least not on the short term. Neither does it include limitations due to geographical potential constraints. These limitations need to be further investigated, e.g. how to include them as well in energy models.
- Experience curves can be used to explore future reduction of production costs. However, experience curves cannot forecast price developments. For example, various renewable electricity technologies display stabilizing or even increasing prices in recent years. These price increases are due to several reasons (see also previous point), but also because policy support has created a strong demand for these technologies, causing supply shortages and rising prices. These effects are not included in experience-curve based scenarios.
- Experience curves for energy demand technologies face several additional dilemmas compared to supply technologies, due to three reasons: i) changing product characteristics, i.e., the technical components of energy demand technologies changed in the decades since these products are sold at the market; ii) energy efficiency improvements and investment costs can go hand in hand but do not necessarily have to: Putting less isolation material in a refrigerator will make it cheaper, but at the same time less energy efficient; iii) the production of energy demand technology has become cheaper in the past due to the outsourcing of production to low wage countries. This is increasingly a way to reduce production costs of consumer appliances, but has little to do with technological learning.
- Experience curve extrapolation holds clear advantages above ‘only’ bottom up studies, but error/uncertainty margins have to be included. Experience curves have been shown to be a valuable tool for both analyzing past developments and quantifying future cost reductions. As was recently shown, they are vastly superior to using time as explanatory variable for forecasts, and they can be especially useful when supported by bottom-up engineering studies. However, especially for long-term forecasts, small variations in PRs can lead to significantly deviating cost reductions in scenarios or completely different model outcomes in energy and climate models. Therefore, calculating error margins in progress ratios is recommended, both to express the quality of the fit (compared to the use of R^2 and as yardstick for optimistic and pessimistic scenarios for future outlooks.
- Experience curves and innovation systems theory may complement each other, a hybrid approach for short to medium-term scenario analysis could be explored. So far, the experience curve approach has been mainly utilized in top-down and bottom-up energy and climate models, for which it is well-suited, as it provides an elegant way to model endogenous technological change. However, while experience curves can quantify cost reductions with cumulative market diffusion, by themselves, they cannot forecast whether the actual market diffusion will occur.

Especially the transition-management approach, applied by Dutch policy makers a few years ago, could possibly benefit from a hybrid approach of quantifying potential future production costs reduction of a new technology, and qualitatively evaluating the current and future chances of success based on the fulfilment of the various functions of innovation. Especially for technologies expected to gain market maturity in the short-to-medium term (e.g. 5-15 years) such an approach would seem promising. While such a hybrid approach needs to be developed in more detail, and does probably pose serious methodological questions to be solved, it could be developed into a valuable tool to support transition management.