



Tranche 1 Study Ω 1/010

**Fuel-Cycle Assessment of Alternative
Aviation Fuels**

Draft final Report, April 2009

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28 April 2009

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Executive Summary

Oil products have fuelled the world's aviation system since the Wright brothers' first successfully powered flight in 1903. The dependence on oil products can be attributed, among others, to their favourable weight/volume characteristics. In addition, for over a century, with the exception of a few price hikes, oil products have been considered abundant and cheap. However, in light of the rising oil import dependence and the recent oil price increase at the beginning of the 21st century, combined with the growing concern about aviation's impact on climate change, the aviation industry has started to look for alternatives to petroleum-derived jet fuel. Over the past year, a number of airlines have started to test a range of biofuel blends.

The purpose of this study was to assess the life cycle characteristics of aviation fuels derived from petroleum and other feedstocks. The considered alternative aviation fuels include jet fuel from unconventional oil (oil sands and shale oil), synthetic jet fuel from coal, natural gas, cellulosic biomass, and micro-algae, and rapeseed-based biodiesel for use as a blending component with petroleum-derived jet fuel. Once certified, these drop-in fuels would not underlie the long lead times for designing, building, and displacing the existing aircraft fleet and fuel infrastructure but allow rapid utilization in existing commercial aircraft. In assessing life-cycle characteristics, this study focused on energy use, greenhouse gas emissions, major material (mainly water) inputs, land-use implications, and supply costs.

The study identifies a wide range of possible petroleum substitutes, being capable of mitigating oil import dependence. However, only few of these alternatives would result in a reduction in lifecycle greenhouse gas emissions. Natural gas based synthetic oil products with carbon capture and storage would reduce lifecycle GHG emissions by a few percent. Significantly larger reduction in lifecycle GHG emissions in the order of 85 percent could be achieved through synthetic oil products from cellulosic biomass. However, the land-use implications of using these biomass-derived fuels would be significant. If the land requirement of the cellulosic biomass, such as willow, is considered, in order to satisfy the 2007 fuel demand in the UK by commercial aircraft of 615000 TJ (Department for Transport, 2008) would require a land area of about 3.8 million hectares, which corresponds approximately to half the size of Scotland. While natural gas-based synthetic aviation fuels have already been tested by the U.S. military, BTL is about to be commercialized and could thus provide an increasingly important fuel stream over the mid term. Both fuels are projected to be available at costs of well below \$100 per barrel.

Owing to their significantly higher productivity, microalgae-based fuels are expected to offer a significant reduction in the land area required for cultivating the fuel feedstocks. However, in order to achieve these levels of productivity, microalgae would need to be supplied with concentrated CO₂, a condition that can increase lifecycle GHG emissions. In today's energy system, power plant CO₂ can be captured and used as an algae feed, thus extending the benefit of fossil fuels beyond electricity generation. However, in the longer term future—the time horizon over which the technological and

economic challenges of microalgae can potentially be resolved—power plant CO₂ may be captured and stored underground. Under such conditions, algae-based fuels would release a similar amount of lifecycle GHG emissions per unit energy than petroleum-derived jet fuel. If the land requirement of algal biomass is considered, with the productivity assumed in this report of 30g/m²/d, satisfying the 2007 fuel demand in the UK by commercial aircraft would require a land area of about 0.3 million hectares, which corresponds to the size of the region of Cambridgeshire.

1 Introduction

For over a century, oil products have been the dominant source of transportation energy. This oil dependency is for good reason. Oil products are liquid at standard temperature and pressure and thus allow easy handling. Given the lack of oxygen atoms, they have a high thermal stability and do not cause corrosion. Perhaps most importantly, oil products also have favourable weight/volume characteristics: gasoline, diesel, and jet fuel have the highest energy content per unit volume of all fuels and the highest energy content per unit mass of all liquids fuels.

Table 1 reports the main physical and chemical characteristics of oil products and a range of alternative transportation fuels. As can be seen, oil products are superior to their possible substitutes in virtually all physical characteristics. Storing a fuel energy amount of 34.7 MJ requires only 1 liter of jet fuel, but would require 1.6 liters of ethanol, 2.2 liters of methanol, and significantly larger volumes of natural gas or hydrogen. Even if liquefying methane or hydrogen, the volume requirements would still be nearly 70 percent and more than 300 percent larger, respectively.

Table 1: Selected physical and chemical characteristics of transportation fuels.
Source: Schäfer et al. (2009), Hileman et al. (2009)

	<i>C/H Ratio</i>	<i>Net Energy Content</i>		<i>Direct CO₂ Emissions</i>	<i>Fuel Density</i>	<i>Sulphur Content</i>	<i>Aromatics Content</i>
	(/)	(MJ/L)	(MJ/kg)	(gCO ₂ /MJ)	(g/L)	(Wt.%)	(Wt.%)
Petroleum-derived oil products							
Jet fuel	0.55	34.7	42.8	74.3	811	≈ 0.05	> 8
Diesel	0.55	35.5	42.5	74.8	835	< 0.005	> 8
Gasoline	0.54	32.2	43.5	73.0	740	< 0.005	> 8
Biodiesel	0.53	32.9	37.5	75.3	860	< 0.002	0
FT diesel	0.47	34.2	43.9	70.9	780	< 0.001	< 1
FT jet fuel	0.46	33.5	44.1	70.4	760	< 0.001	< 1
Alcohol fuels							
Ethanol	0.33	21.3	26.8	71.4	795	< 0.001	0
Methanol	0.25	15.6	19.7	69.8	790	< 0.001	0
Methane							
CNG ^a (248 bar)	0.25	10.4	50	55.0	208	< 0.001	0
LNG ^b	0.25	21.0	50	55.0	420	< 0.001	0
Hydrogen							
CH ₂ ^a (345 bar)	0.00	2.8	199.9	0.0	23.0	0	0
LH ₂ ^b (20 K)	0.00	8.5	199.9	0.0	70.8	0	0

Notes:

^a Compressed

^b Liquid

Although petroleum products satisfy best the various requirements of transportation fuels, two main issues have emerged that spur the search for alternatives. One is the geographic location of oil reserves outside the

industrialized world. As with the U.S., Western Europe currently imports nearly 70 percent of its oil and the majority of these oil imports are from only a small number of politically less stable Middle Eastern economies. Over the past three decades, each oil price hike has caused macroeconomic losses. In commercial aviation, these variations in oil price have caused fuel costs to account for between 25 and 65 percent of the direct operating costs plus investments. Thus, as with the macroeconomic losses, a rise in the oil price can have a significant impact on airline balance sheets. Another reason to look for alternatives to petroleum-derived jet fuel is the rising contribution of the airline industry to climate change. Burning one kg of jet fuel forms nearly 3.2 kg of carbon dioxide¹ (CO₂) and although aircraft currently account for only about 3 percent of global energy-related CO₂ emissions, the comparatively high growth rates underlying air traffic suggest that this share may increase in future.

Several alternative fuels could offer a solution to both concerns. As can be seen from Table 1, all non-petroleum fuels have lower levels of direct CO₂ emissions, ranging from 5 percent for synthetic petroleum products to 100 percent for hydrogen. However, since all fuels shown in Table 1 can be produced from different feedstocks using different processes, the associated upstream emissions need to be also considered. The purpose of this report is to perform a lifecycle analysis of energy use, GHG emissions, and costs of the major alternatives to petroleum-derived jet fuel. In addition, as will be shown below, the feedstocks suitable for producing these alternative fuels are distributed more equally, potentially leading to increased levels of energy security and reduced price volatility.

However, substituting aviation fuels is not straightforward. Not only are these fuels subject to tight specifications, aviation fuels are also used as a hydraulic fluid in engine control systems and as a coolant for certain fuel system components and hence, thermal stability becomes an essential property of the fuel. In addition, aviation fuels contain a number of additives to enhance or maintain its properties, including antioxidants (to prevent oxidation during fuel storage), antistatic agents (that increase the conductivity of the fuel to enhance the dissipation of static electricity generated by fuel movements through fueling systems and thus prevent sparking), corrosion inhibitors, and icing inhibitors that prevent icing of water precipitated at the cold temperatures at high altitudes (Chevron, 2006 (1)). These factors, although essential for the certification of an aviation fuel, are out of the scope of this project due to the limited time budget.

Among the various fuels listed in Table 1, this study focuses on drop-in fuels, i.e., those fuels that can be used without major modifications to the existing airframe/engine and fuel infrastructure. The reason underlying this choice is of practical nature. Aircraft experience an economic life of about 40 years. This suggests that it takes several decades until new technology enters the fleet on a scale sufficient to make a difference. The long time scales limit the number of alternative aviation fuels to make an impact over the short to medium term. Alcohols and cryogenic fuels are thus not

¹ This value depends solely on the mass fraction of carbon in the fuel.

considered in this report. The main drawback of the former is their low energy content (per unit weight and volume), resulting in an aircraft with strongly reduced range. For hydrogen, the main disadvantage is the very low energy per unit volume, even if liquefied. Hydrogen aircraft would thus require completely new designs (both engine and airframes) in addition to a new fuel infrastructure.

The drop-in fuels that are covered in this report include synthetic oil products from fossil and cellulosic biomass feedstocks, hydrogenated oils and biodiesel as blending components. The evaluation carried out in this report follows a lifecycle approach, which includes a well/mine/soil-to-wake study of the entire fuel chain from initial feedstock harvesting/extraction, to fuel production, transportation and combustion in the aircraft engine. However, limiting the lifecycle analysis to only energy use, GHG emissions, and costs would overlook other important evaluation criteria. For drop-in fuels, these include market penetration time, environmental impacts other than GHG emissions, and contributions to energy independence. Further criteria are material and water requirements, which can be important considerations for some of the fuels from unconventional oils and biomass. Due to the limited resources available for this study, we cannot examine each of the additional concerns in detail, but only discuss those in passing.

Oil companies and airlines are currently teaming with engine and aircraft manufacturers to demonstrate the feasibility and potential for the use of alternative fuels for aviation. The first test flight was carried out in February 2008 with a commercial jet flying on alternative fuel. An Airbus A380 performed a three hours test flight powered on a blend of regular fuel and fuel processed from gas. The most recent of these test flight was carried out at the end of January 2009 on a Boeing 747-300 with one of the engines being powered with a 50% biojet blend. In the Appendix 1, the lifecycle GHG emissions of the recent test flights with alternative fuels will be calculated.

The Resource Base

Table 2 summarizes an estimate of the resource base (reserves and resources) of conventional and unconventional oil and the reserves for coal, natural gas, and biomass. All reserve and consumption estimates of fossil fuels relate to 2007, while biomass data are projections for 2030. Note that the reserves are those occurrences that can be exploited economically with current technology at prevailing market conditions. In contrast, the oil resources are either too expensive, or too difficult (or a combination of both) to be extracted now. Rising oil prices, however, are likely to continue to induce technological change and make the exploitation of a growing amount of resources cost-effective, a condition which will transfer resources to reserves.

Table 2 shows the large amount of total fossil occurrences with reserve-to-production ratios between 40 years (oil reserves) and more than 700 years (coal). But even if focusing on oil occurrences only, the amount of feedstocks in the ground is vast. Oil resources more than double the amount of reserves, while the feedstocks of unconventional oils (bitumen, heavy oils, and shale oil) would increase oil reserves nearly tenfold. In contrast, the

projected biomass reserves (which include forest and agricultural waste and biomass plantations) correspond to only 2 percent of the oil reserves. Biomass reserves are also smaller than world oil consumption in 2007, a relation that becomes even significantly less favorable if also taking into account the conversion losses from biomass to biofuels. This condition suggests that biofuels would only be able to play a limited role in the fuel market.

Table 2: Estimates of the resource base of light oil and unconventional oil (bitumen, heavy oil, and shale oil), reserves of coal, natural gas, and biomass and their consumption in 2007

	Oil Reserves	Oil Resources	Bitumen	Heavy Oil	Shale Oil	Coal	Natural Gas	Biomass per annum in 2030
Occurrences								
World								
Bln. boe	1,238	1,418	5,497	3,396	2,819	4,348	1,170	18–35
Bln. toe	169	193	750	463	385	593	160	2–5
EJ	7,071	8,100	31,400	19,400	16,100	24,838	6,683	100–200
% UK	0.3	1.3	0.0	0.0	0.1	0.0	0.2	0.1
% EU	0.5	3.7	0.3	2.1	3.1	3.4	1.5	10
% US	2.4	11.1	0.3	6.2	73.9	28.6	3.4	12–13
% M. East	61.0	39.5	0.0	28.4	1.2	0.2	41.3	0.6–0.7
Current Production								
World								
Bln. boe	27	0	0.5	2.5	≈ 0	6	19	² 0.6
Bln. toe	4	0	0.1	0.3	≈ 0	1	3	–
EJ	154	0	3	14	≈ 0	35	110	0.6
RP Ratio, World	¹ 41	–	11,000	1,358	–	715	61	–

Sources: BP (2008), Meyer and Attanasi (2003), Patlsev et al. (2005), IEA (2006)

Notes: ¹ includes bitumen and heavy oil production, ² in terms of final (biofuel) energy

Table 2 illustrates that total occurrences of oil reserves and resources are plentiful. However, in relation to their consumption, strong disparities exist on a regional level. For example, the U.S. accounts for only some 2 percent of global light oil reserves, but consumes nearly one-quarter of the total level. Similarly, the EU owns only 0.5 percent of global light oil reserves, but consumes 15 percent. The global biomass potential in 2030 of 100-200 EJ already indicates the limited availability of (primary) energy compared to the current consumption of crude oil in the order of 178 EJ. However, as discussed below, biomass-based fuels can become an important fuel stream.

2 Life-Cycle Analysis

In the following, we analyze the upstream characteristics of synthetic jet fuel from petroleum and natural gas (well-to-tank), oil sands, shale oil, and coal (mine-to-tank), and biomass (soil-to-tank). We also show soil-to-tank results for biodiesel fuels from rapeseed and water-to-tank results from microalgae in

terms of energy use, GHG emissions and costs. Already, a number of test flights have been carried out using different blends of biofuels to assess their effects on the engine and the aircraft's fuel systems. These cases will be discussed in Appendix 1.

We begin with energy use. The energy use of individual processes is calculated via their thermal efficiencies. The overall energy use of the supply chain then results from the sum of the energy use of all components.

The related CO₂ emissions consist of two components. One component can be attributed to the ratio in fuel carbon leaving a conversion process to that entering the process, that is, the carbon efficiency. The second component of CO₂ equivalent emissions consists of non-CO₂ greenhouse gases, which here include methane (CH₄) and nitrous oxide (N₂O). CH₄ emissions result from coal, oil, and natural gas extraction, and the transport of natural gas. We assume methane emission factors of 0.05 grams of methane per MJ of extracted crude oil, 0.1 grams per MJ of extracted coal, and 0.2 grams per MJ of methane. In contrast, N₂O emissions are released from agricultural soils through the use of fertilizer following microbial oxidation or reduction processes of nitrogen compounds. Table 3 summarizes the major results of the lifecycle analysis.

2.1 Jet fuel

Jet fuel consists of the kerosene fractions of crude oils, which are between those of naphta (lower boiling temperature) and diesel (higher boiling temperature). The fuels presented in this section cover jet fuel from light oil as a reference point, those from unconventional oil sources and synthetic fuels via Fischer-Tropsch synthesis with different feedstocks.

Light Oil

As a reference point, we use jet fuel from light oil. The fuel cycle energy use, which takes into account oil extraction, refining, and transport to the airport results in about 0.13 MJ per MJ of jet fuel. The most significant determinant of these numbers is the refinery efficiency, here assumed to be 91 percent. This number can only be considered as typical, because it depends on the composition of crude oil (gravity, sulphur content, etc.), the refinery structure, the mix of oil products produced, along with other factors. For example, the use of heavier crudes requires more jet fuel to be produced from cracking longer carbon chains compared to light crudes; this would reduce the refining efficiency, all other factors equal. The associated fuel cycle GHG emissions result in about 10.7 gCO₂-eq per MJ of jet fuel. Nearly 90 percent of these emissions result from energy conversions, while the remaining share can be attributed to methane leaks in the oil field (see Schäfer et al., 2009). In combination with the GHG emissions associated with fuel combustion, i.e., 74.3 gCO₂ per MJ of jet fuel as shown in Table 3, total lifecycle GHG emissions result in 85.0 gCO₂-eq per MJ of jet fuel.

Oil Sands

Natural bitumen (oil sands) shares the same formation history as conventional crude oil. However, these deposits were degraded through

bacteria attacks and erosion, and thus lost the light components over the course of millions of years. After extracting oil sands through surface mining, hydrocarbon compounds are separated from sands and clay. This process is material intensive. Producing one barrel of synthetic crude, which weighs about 140 kg, requires roughly 2,000 kg of oil sands and three barrels of water. Unconventional oils contain comparatively large amounts of nitrogen, oxygen, sulfur, and heavy metals, which require special treatment, separation, and handling facilities at refineries. In contrast, bitumen from deeper reservoirs is soaked with steam to reduce its viscosity and enable conventional oil production. As with the upgrading process in a refinery, the long carbon chains of these substances are broken down into shorter ones. According to field data from the Canadian oil sand program, the average energy use for extracting and upgrading the bitumen (using the weighted average of surface mining and steam injection into deep reservoirs) corresponds to one-quarter of the synthetic crude oil's energy content, or 0.25 MJ per MJ of synthetic crude oil. Combining oil refining and product distribution, fuel-cycle energy use is about 0.38 MJ per MJ of jet fuel. The related GHG emissions result in about 26.0 gCO₂-eq per MJ of jet fuel. Taking also into account the GHG emissions associated with fuel combustion, i.e., 74.3 gCO₂ per MJ of jet fuel as shown in Table 3, total life-cycle GHG emissions result in 100.3 gCO₂-eq per MJ of jet fuel, i.e., 18 percent above that of petroleum-derived jet fuel.

Shale Oil

In contrast to the overmature oil sands, oil shale (a mixture of calcium carbonate and clay) contains a hydrocarbon compound, kerogen, which is a precursor of crude oil. Given favorable conditions, i.e., sufficient reservoir depth to ensure high temperatures and pressures, the immature kerogen would convert naturally over the course of millions of years. Thus, all efforts to process kerogen into shale oil attempt to accelerate the geological clock through providing these conversion conditions. The solid oil shale rock is mined like coal, both underground and from the surface.² As with the bitumen-based processes, the shale oil process is material intensive, requiring similar amounts of raw material and water per unit shale oil. Unlike other processes, during retorting, in which the shale oil is produced under elevated temperatures, the oil shale's calcium carbonates and magnesium carbonates are reduced to CO₂, which adds to the fuel-cycle GHG emissions. Based on the composition of Estonian shale oil, this CO₂ accounts for 18% of total fuel-cycle CO₂ emissions. Assuming a retorting efficiency of 70%, which is representative of the US shale oil program in the 1980s, fuel-cycle GHG emissions result in excess of 80 gCO₂-eq/MJ-or nearly 8 times the level of

² Underground or "in-situ" oil shale production methods have been tested, but they come with significant challenges. Similar in principle to the hot extraction of bitumen from deeper reservoirs, this strategy would try to provide a sufficient amount of process heat in a number of ways: through controlled nuclear underground explosions, underground combustion, or more recently, through electric heating elements submersed in bore holes. However, in-situ retorting is still in the pilot stage — and it raises a range of additional environmental concerns, including ground water contamination.

petroleum-derived jet fuel. Adding the CO₂ emissions associated with the combustion of jet fuel, life-cycle emissions result in 155 gCO₂-eq per MJ of jet fuel, a level that is more than 80 percent above that of petroleum-derived jet fuel. Currently, shale oil programs are operating in Brazil and China. Many other shale oil programs, including those in the US and Australia, have been abandoned because of the low profitability during periods of low oil prices. However, the enormous resources especially in the U.S. are likely to attract further commercial interest, at least over the longer term.

Coal-based Synthetic Oil Products

The commercial production of synthetic fuels from coal has a long history. During World War II, England, Germany, and Japan generated a significant amount of synthetic oil products. South Africa developed coal-to-liquid plants during the 1950s to the 1970s and still operates all three facilities, supplying, among others, Johannesburg airport with synthetic jet fuel.

The conversion of coal or any other hydrocarbon feedstock to liquid fuels begins with breaking down these feedstocks' hydrocarbon molecules into hydrogen and carbon monoxide. This decomposition is accomplished by subjecting the feedstock to high temperatures and pressures in the presence of steam and a catalyst, and under a controlled supply of oxygen. The synthesis gas that results from this process is cleaned of impurities and then subjected to additional processing. This step, the Fischer-Tropsch synthesis, further rearranges the molecules to generate a spectrum of hydrocarbon fuels, i.e., naphtha (a gasoline feedstock), kerosene, diesel fuel, and higher blending materials such as waxes. In addition to being a proven technology, this process produces a high-quality fuel. For example, the removal of nitrogen, sulfur, and particulates from the synthesis gas makes it possible to generate low-aromatic, cleaner-burning synthetic oil products—which, in turn, release lower levels of air pollutant emissions when burned. The significantly lower aromatics contents compared to oil products can be seen in Table 1.

As an alternative to the indirect process, coal liquefaction can follow a direct process. However, modern direct liquefaction is still in the laboratory stage.

Because the indirect process works at the molecular level, i.e., decomposes the carbon-hydrogen chains and rearranges the molecules in the desired way, the fuel-cycle energy use is comparatively high, about 1 MJ per MJ of jet fuel. (We assume a coal-to-liquids conversion efficiency of 50 percent). Fuel-cycle GHG emissions result in about 115 gCO₂-eq per MJ of jet fuel, more than 10 times the level of petroleum-derived jet fuel. If adding the CO₂ emissions associated with the combustion of jet fuel, life-cycle emissions result in about 190 gCO₂-eq per MJ of jet fuel, nearly twice the level of petroleum-derived jet fuel.

This high emissions level can be drastically reduced. A carbon capture and storage (CCS) unit could reduce CO₂ emissions of the coal refinery to levels only slightly above those of petroleum-derived jet fuel. Under such condition, fuel-cycle GHG emissions would result in nearly 90 gCO₂-eq per MJ

of jet fuel, which compares to 85 gCO₂-eq per MJ of petroleum-derived jet fuel.

Natural Gas-based Synthetic Oil Products

Compared with the long history of CTL conversion, the history of commercial gas-to-liquids (GTL) production is significantly shorter. After the first commercial-scale GTL plant was built by Shell in Malaysia in 1993, today several plants are operating in the remote areas of the world where “stranded” natural gas, natural gas that is abandoned or burned off because there is no economical way to transport it, would require enormous investments to be moved via pipeline or to be liquefied and shipped to markets.

The production process of synthetic oil products from natural gas follows that of coal liquefaction, i.e., the generation of a synthesis gas, followed by a Fischer-Tropsch synthesis. Because natural gas is already in a gaseous state at standard temperature and pressure, energy requirements are smaller compared to the coal-based process. Fuel-cycle energy use results in about 0.68 MJ per MJ of jet fuel. (We assume a gas-to-liquids conversion efficiency of 60 percent). The related GHG emissions result in nearly 25 gCO₂-eq per MJ of jet fuel. In combination with the CO₂ emissions associated with the combustion of jet fuel, lifecycle GHG emissions result in about 99 gCO₂-eq per MJ of jet fuel, 16 percent higher than those of petroleum-derived jet fuel.

If employing CCS technology, fuel-cycle CO₂ emissions can be reduced to about 5.8 gCO₂-eq per MJ of jet fuel, a level significantly below that of petroleum-derived jet fuel.

Cellulosic Biomass-based Synthetic Oil Products

In theory, all biomass-based fuels could emit very low levels of net life-cycle GHG emissions. In the hypothetical case of a pure biofuel economy, where all energy inputs into the production and supply of biofuels are produced in a renewable fashion, the fuel cycle and combustion-related GHG emissions would be absorbed by subsequent generations of crops. However, most current biofuels require a significant amount of fossil energy input during the production stage, a condition that increases lifecycle GHG emissions.³ Current generation biofuels also compete for agricultural land that could otherwise be used for food production, at least to some extent.

In contrast to most current-generation biofuels, second-generation biofuels (i) are largely energy independent through the use of biomass co-products as a source of process energy (instead of a feedstock supplying the food industry) and (ii) can be grown on marginal land that does not compete with food production. Cellulosic biomass, such as willow and hybrid poplar, are the main examples of a feedstock used for second-generation biofuels.

³ A significant concern associated with biofuels is related to the soil and plant carbon that would be released with the conversion of forests, peat lands, savannas, or grassland to new cropland. This outcome can be avoided if producing biomass feedstocks more intensively on existing land or through converting degraded or abandoned agricultural into biomass plantations. Similarly, the conversion of plant residues or organic waste would cause little or no extra CO₂ emissions.

External energy use associated with growing cellulosic biomass and transporting the crops to the processing plant is some 7 GJ per hectare (Farrell et al., 2006). Assuming a biofuel yield of 5,000 liters of fuel per hectare per year and an energy content of 35 MJ per liter of fuel, fuel cycle energy use results in about 0.04 MJ per MJ of jet fuel. The conversion process, following the coal-to-liquids process, draws most of its energy requirements from the biomass input. The associated fuel-cycle GHG emissions account result in 12.8 gCO₂-eq per MJ of jet fuel. Because the CO₂ emissions generated during fuel combustion are absorbed by subsequent generations of biomass plantations, the fuel-cycle emissions correspond to life-cycle emissions. The first commercial biomass-to-liquid plant is currently under construction in Germany.

Fatty Acid Methyl Esters

Biofuels can also be produced from vegetable oils and animal fats. The oils and fats are triglycerides of fatty acids and the process of producing biodiesel involves the transesterification of these triglycerides with methanol to produce fatty acid methyl esters (FAMEs) and, as a by-product, glycerol (Christi, 2007). These esters have physical and chemical properties that are similar to conventional diesel fuel. However, some properties of biodiesel also depend on the particular feedstock properties. This could be a drawback for the use of FAMEs as aviation fuels given the tight specifications to which the latter are subjected. FAMEs also contain small amounts of oxygen. Thus, not only is their energy content per unit weight slightly lower than that of conventional kerosene, FAMEs are also subject to increased bacteria growth during storage, resulting in reduced shelf life compared to (synthetic) oil products. In addition, biodiesel's freezing point is near 0°C, significantly higher than that of jet fuel of -40°C. This is a critical limitation, as aircraft fuel is exposed to very low temperatures at cruise altitude. Even blends of biodiesel with jet fuel have a significantly higher freezing point than neat jet fuel, a condition that may not be sufficiently resolvable with additives.

Owing to the difference in climatic and soil conditions, the crops used for biodiesel production differ across different parts of the world. In the U.S., soybean oil is the largest source for biodiesel. In contrast, rapeseed is normally used in Europe, whereas in Asia, palm oil and coconut oil are the most usual feedstocks. More recently, relatively unknown crops, like jatropha and camelina have been gaining importance, partly because they do not compete with food crops. The data presented in Table 3 is representative for the conversion of rapeseed oil to FAME (Thijssen, 2006; Concawe, 2007). The energy balance of the fuel cycle is about 1.2 MJ per MJ of jet fuel, of which 70 percent can be attributed to the FAME manufacturing. The cultivation of the rapeseed contributes to a further 24 percent of the final figure. Lifecycle GHG emissions of FAME from rapeseed result in about 65 gCO₂-eq per MJ of jet fuel with the majority of that amount being due to the cultivation process. This is due to the large amount of fertilizers required to cultivate rapeseed.

Hydro-treated Vegetable Oils

Recently, a novel process has been presented by UOP and ENI S.p.A. (UOP/ENI Ecofinig™) to produce a paraffinic diesel fuel from vegetable oil (Kalnes, 2007), thus overcoming some of the drawbacks of the FAMES presented above. The resultant biofuel is claimed to have good cold flow properties and storage stability and its properties are independent of the starting feedstock (and therefore, a higher percentage of biofuel can be used in blends). In a first (hydrogenation) step, the oxygen molecules of the triglycerides are removed with hydrogen to produce a pure paraffinic hydrocarbon. The primary co-product of the process is propane and the by-products are water and carbon oxides (Holmgren *et al.*, 2007). In a subsequent step, the diesel quality is controlled by isomerizing the paraffins (Kalnes *et al.*, 2008). In a final selective cracking process, a slightly lighter "Green Jet" aviation fuel can be obtained (Holmgren, 2008). Some of the current test flights have used a blend with hydrotreated vegetable oil provided by UOP.

The feedstock for the production of the hydrotreated vegetable oils would be the same as for the production of FAMES (see section above).

The estimation of the energy balance and GHG emissions, the hydrotreating process should be compared with a FAME of the same feedstock in order to assess the differences between the two fuel paths. According to Wong (2008), the energy requirements and GHG emissions of the hydrotreating process applied to soy oil are about 4.44MJ/kg fuel and 8.9 gCO₂-eq per MJ fuel respectively. For a FAME based upon the same feedstock, the energy requirements and GHG emissions were calculated by Prabhu *et al.* (2008) as 6.47 MJ/kg fuel and 2.7 gCO₂-eq per MJ fuel, respectively. However, these results depend, amongst others, on the different paths followed to obtain the hydrogen and the methyl for the hydrotreating and the FAME processes respectively. Nevertheless, the limitation of the percentage of FAME in the blends of aviation fuels represents an important disadvantage compared to hydrotreated fuels that could potentially be introduced as a full substituent of the current petroleum derived fuels.

Micro-Algae

The production of liquid fuels from microalgae has recently attracted much interest due mainly to the potentially high levels of productivity, a characteristic that mitigates the land requirements and potential competition with food production of especially first-generation biofuels. However, to ensure high productivity, unlike conventional terrestrial crops, CO₂ has to be fed to the algae. Given the novelty of the system, it will be explained in detail in section 3. The data presented in this Table are representative of hydrogenated algal oil. The productivity assumed in this study corresponds to an algae growth rate of 30 g/m²/day with a lipid content of 50 percent. This value, which corresponds to about 375 bbl of jet fuel per ha, has often been used as the reference point in techno-economic analyses carried out in the past (Weissman and Goebel, 1987 and Benemann and Oswald, 1996). According to Benemann (2008) such yield can only be achieved through sustained R&D efforts. The values presented in Table 3, which will be

explained in detail in the case study presented in section 3, correspond to two different reference conditions, depending on whether there is a carbon capture and sequestration (CCS) unit associated to the source of CO₂.

The higher value of the fuel cycle energy use range of 0.44 MJ/MJ_{product} corresponds to a case in which the CO₂ necessary to fertilise the algae is derived from a coal power plant without a CCS unit. In this case, the CO₂ feed is attributed to the coal power plant and lifecycle GHG emissions result in 32 gCO₂-eq per MJ fuel, which is within the indicated range in Table 3 and discussed below. This value is less than 40 percent compared to that of petroleum-derived jet fuel. In contrast, if the coal power plant-CO₂ emissions are sequestered, the CO₂ feed is attributed to the algae fuel and lifecycle GHG emissions result in 86 gCO₂-eq per MJ fuel, a level similar to that of petroleum-derived jet fuel. The lower end of the lifecycle GHG emissions range of 19 gCO₂-eq per MJ fuel corresponds to a case in which clean flue gas instead of purified CO₂ is being used to fertilise the algae. This case is discussed below. The large investment cost and the high cost of purifying CO₂, amongst other factors, are reflected in the final price of the fuel.

Summary

Table 3 reports the main lifecycle characteristics of jet fuel from various feedstocks and rapeseed-based biodiesel that could be used as a blending fuel. Compared to petroleum-derived jet fuel, fuel cycle energy use is larger for any alternative, ranging from a tripling (oil sand derived jet fuel) to a level nearly ten times as high (coal-based synthetic fuels with carbon capture and storage and biodiesel from rapeseed). In the case of fossil fuel feedstocks, similar ratios apply to fuel cycle GHG emissions. Among all fuels, fuel cycle GHG emissions are largest for coal-based synthetic fuels. The second highest fuel cycle GHG emissions are released by the shale oil process, where a significant fraction of GHG emissions is formed during retorting, when the oil shale's calcium carbonates and magnesium carbonates are reduced to CO₂. However, fuel cycle GHG emissions can be decoupled from energy use through carbon capture and sequestration. In such case, fuel cycle GHG emissions from coal-based synthetic oil products are only marginally higher than those from petroleum-derived jet fuel, while those from natural gas-based jet fuel would be even lower than those from petroleum-derived jet fuel. If adding the CO₂ emissions associated with fuel combustion, *i.e.*, 74.3 gCO₂/MJ in the case of petroleum-derived jet fuel (see Table 1), the variations in fuel cycle GHG emissions are mitigated for fossil fuel-based feedstocks. Compared to petroleum-derived jet fuel, the lifecycle GHG emissions then range from roughly minus 10 percent in the case of natural gas-based synthetic jet fuel with carbon capture and storage to slightly more than a doubling for coal-based synthetic jet fuel without carbon capture and storage. In the case of synthetic jet fuel from cellulosic biomass, fuel cycle GHG emissions relate to those from the lifecycle, as the combustion-related CO₂ emissions are being absorbed by subsequent generations of biomass crops. Lifecycle GHG emissions from synthetic jet fuels produced from microalgae strongly depend upon the accounting of the CO₂ feed. The lower end corresponds to a scenario when the corresponding CO₂ source does not

have an associated carbon capture and sequestration (CCS) unit, while the higher end reflects a scenario in which a CCS unit is associated to the CO₂ source (see Section 3). In both cases, the productivity assumed corresponds to an algae growth rate of 30 g/m²/day with a lipid content of 50 percent, which represents a 10-fold oil yield over today's state of technology (about 10 g/m²/day with a lipid content of 15 percent (Sheehan *et al.*, 1998)).

Assuming fuel delivery costs of \$0.05 per liter, the fuel production and delivery costs in Table 3 range from \$25-30 per barrel of synthetic crude oil in the case of oil sand or natural gas feedstocks to \$85 per barrel for shale oil or cellulosic biomass feedstocks. Over the past 10 years, the oil price has stretched over this entire range of prices. For the rapeseed, the high cost is a result of the large amount of fertilizers needed for this particular feedstock. The high cost of the fuels from microalgae reflects partly the high capital and operational cost of technologies currently in development as well as the large cost associated with the conditioning of the CO₂ needed as algae feed (see case study in section 3).

Table 3 also reports the energy yield per unit land area. For fossil fuels, this indicator is within one order of magnitude. However, in order to produce a given amount of synthetic oil products, three orders of magnitudes more land would be required for biofuels. Also shown is the amount of water required to produce one unit of fuel. While water use is essentially zero in petroleum-based processes, it can be significant for fossil feedstock-based synthetic fuels, and vast for biofuels.

Table 3: Typical fuel- and life-cycle characteristics of jet fuel and biodiesel from various feedstocks

Feedstock	Jet Fuel								Biodiesel	
	Petro- leum	Oil Sands	Shale Oil	Coal		Natural Gas		Cellulosic Biomass	Micro- algae	Rape- seed
Carbon Capture & Storage	none	none	none	none	yes	none	yes	none	none	none
Fuel-cycle energy use, MJ/MJ _{Product}	0.13	0.38	0.58	1.02	1.10	0.68	0.75	0.05	0.10-0.44	1.20
Fuel-cycle GHG emissions, gCO ₂ -equivalent/MJ _{Product}	10.7	26.0	80.9	115.3	15.5	24.8	5.8	12.8	20-86	65
Life-cycle GHG emissions, gCO ₂ -equivalent/MJ _{Product}	85.0	100.3	155.2	185.7	85.9	95.2	76.2	12.8	20-86	65
Other Characteristics										
Fuel supply costs, \$/L ¹	≈ 0.49	0.3-0.4	0.6-0.7	0.4-0.5	0.4-0.5	0.2-0.3	0.2-0.3	0.2-0.5	>0.8	1.0
Energy yield, 1000 bbl _{Product} /ha/y	N/A	270	1,800	90	85	N/A	N/A	0.03	0.4	0.008
Water use, bbl _{Water} /bbl _{Product}	≈ 1	≈ 4	≈ 4	10-60	10-60	2-7	2-7	1-40	1,000-9,000	≈ 0 ²

Sources: Aden (2007), Chan *et al.* (2006), Schäfer *et al.* (2009), Concawe report (2007), Benemann and Oswald (1996).

Notes: Water use relates to refining (petroleum-derived jet fuel); feedstock extraction, synthetic crude production, and refining (oil sands, shale oil); coal mining and washing, coal-to-liquids conversion (coal); gas-to-liquids conversion (natural gas); land irrigation and biomass-to-liquids conversion (cellulosic biomass). Note that water requirements can vary significantly for especially coal mining (depending upon surface mining with or without land reclamation or underground mining), liquids production (plant design, gasifier technology, etc.), and irrigation requirements (here assumed to be a range of essentially zero to the average of corn production requirements). The values of jet fuel from hydrotreated microalgae oil correspond to two different reference points, depending on whether or not there is a carbon capture and sequestration (CCS) unit associated to the source of CO₂. The productivity assumed in this study is 30g/m²/day and 50% lipid content.

¹ The reference oil price is \$(2005) 50/bbl. The costs for refining and distribution and marketing are assumed to be \$(2005) 0.16 per liter. While carbon capture and storage adds another \$5 per barrel, these costs are not visible because of the low number of significant digits. ² The amount of irrigation water is assumed to be negligible, given that rapeseed is a native feedstock in Europe. The water requirements by the FAME process are very small (Glisic and Skala, 2008).

3 Microalgae as a feedstock for the production of alternative aviation fuels

One key motivation for considering microalgae as a feedstock for the production of biofuels is the fact that their cultivation would unlikely compete with food production given that they can be grown on non-arable land, also in conjunction with the use of wastewater. Algae also offer unprecedented levels of productivity. Compared to terrestrial crops, microalgae may yield about one order of magnitude more fuel energy per unit land area. In comparison with higher order plants where a large percentage of the biomass carries out structural functions, algae mainly produce the cell organelle responsible for photosynthesis, growth and reproduction. Thus, microalgae are more efficient converters of solar energy than higher order plants and macroalgae⁴. As with higher order plants, microalgae need sunlight, water, CO₂ and nutrients to grow and reproduce. Their cultivation in a liquid environment where the cell grows in aqueous suspension allows them better access to the nutrients.

Microalgae fuel research dates back to the 1960s, but it was not until the National Renewable Energy Laboratory (NREL) funded the Aquatic Species Program (ASP) in the late 1970s that comprehensive research was carried out. The ASP program started off by employing large-scale algae plants as CO₂ sequestration units given the high productivity values obtained in laboratory environments and the large amount of CO₂ that algae demand to keep up such productivity. However, the high percentage of lipids found in some algae strains redirected the attention of the ASP to the production of liquid fuels. After almost 20 years of research, thousands of algae strains screened, and large investments directed into the creation of medium size algae plants, low oil prices caused the ASP to terminate. The outcome of this program was presented in Sheehan *et al.* (1998) and has become a landmark of the research of the production of liquid fuels from microalgae. The overall conclusion was that low-cost production of biofuels from algae was not likely to be feasible within the near or medium term. The need for a lifecycle analysis, the failure to identify a lipid accumulation trigger that did not slow down the growth rate, the necessity of keeping the algae cultures free from contamination, along with other challenges (engineering, biological and economic) were additional key findings of this research program. In fact, the engineering, biological and economic barriers have prevented the large-scale development of the algae production systems until today.

The oil yield from an algal plant depends, amongst other factors, on the growth rate and the lipid content of the algae. These two factors cannot be optimized in isolation, as the best known trigger of lipid production, i.e., nitrogen starvation, only enhances the lipid accumulation at the expense of plant growth (Tornabene *et al.*, 1983; Sheehan *et al.*, 1998). Since the

⁴ The photosynthetic efficiency of algae is higher than that of terrestrial crops: an average of 6–8% compared to an average of 1.8–2.2% (Aresta *et al.*, 2005).

closure of the ASP, technology, especially bioengineering, has advanced, including progress in the enhancement of biosynthesis through identifying triggers of lipid accumulation that do not slow down the growth rate and the engineering of light-harvesting antennae. Some of these accomplishments are summarised in Rosenberg et al. (2008). Given the drivers presented in previous sections, there is a rising interest in the production of biofuels from algae. NREL has renewed its efforts in this area (Pienkos, 2007) and is collaborating with Chevron to produce transportation fuels from algae (NREL, 2007).

Algae as a feedstock for alternative aviation fuels

The types of lipid molecules contained in the algae that are conventionally sought out are triglycerides (TAGs). These can be processed to FAMES via transesterification or to paraffinic fuels through hydrogenation.

Three main technical and economic challenges exist with regard to the production of fuels from microalgae (Weissman and Goebel, 1987). These are the cost and availability of water and CO₂ (the two principal inputs into the system), the cost of constructing, operating and maintaining the system, and the design of low-cost processes for the harvesting and processing steps.

3.1 Algae Production Systems

Microalgae have been produced in open ponds and closed bioreactors. Depending on the algae strain, they can be grown in saline or fresh water. Figure 1 presents a conventional open pond algae fuel production system. It consists of the ponds where the algae grow, a source of CO₂, algae harvesting, oil extraction and fuel processing systems and an anaerobic digester that produces methane from algae co-products. As in the example shown in Figure 1, the methane can be burned to produce electricity or used within the algae plant as a source of heat. In this report the source of CO₂ is assumed to be a generic coal power plant. Two different cases will be investigated. These correspond to whether or not there is a CCS unit associated to the source of CO₂. In the following, we briefly describe major components of such an algae fuel plant and some of its alternative configurations.

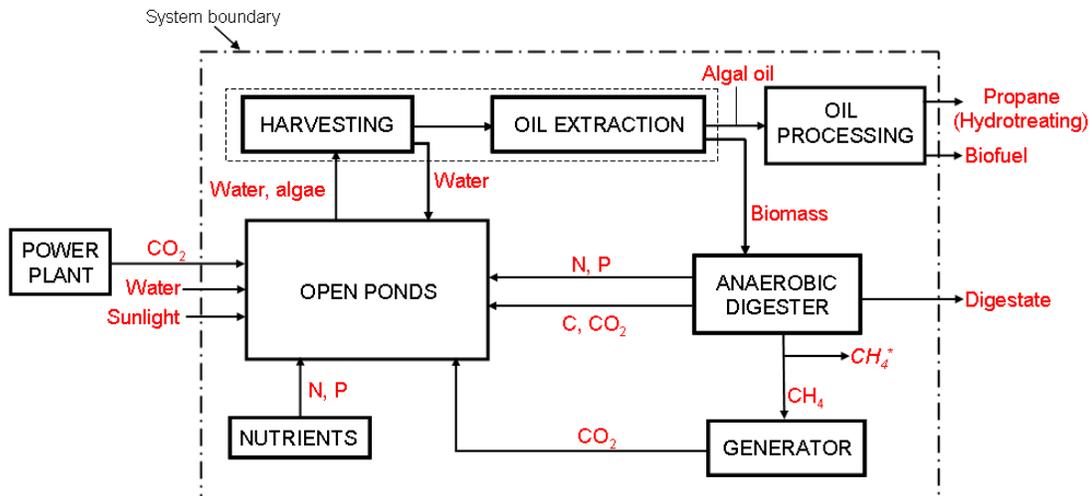


Figure 1: Conventional algae open pond system for fuel production. N = Nitrogen, P = Phosphorus

Over the last 50 years, most algae have been cultivated in open shallow ponds exposed to the atmosphere in areas of high solar insolation. The raceway open pond system is widely considered to be the most cost-effective layout for algae production (see Benemann *et al.* (1982), Weissman and Goebel (1987), Benemann and Oswald (1996)). According to Benemann *et al.* (1982), five criteria need to be met for the site selection of the open systems: climatic, topographic, soil, infrastructure and environmental. The most important climate factors are total insolation and a moderate seasonality. According to van Harmelen and Oonk (2006), an annual average temperature of 15°C or higher would be necessary. In addition, the availability of cheap land and water/wastewater/saline resources in conjunction with CO₂ supplies are of crucial importance.

Open ponds are normally recirculating raceways in which the algae culture is stirred and recirculated by a paddlewheel to enhance the CO₂ absorption. The choice of the right parameter values of the open pond like shape, method of circulation, depth, length and width are crucial to determining the economics of the open pond culture systems (see Benemann *et al.* (1982) for details). Highest algae productivities can be achieved using small-depth ponds (about 10 cm), where the sunlight can reach a larger part of the cultivation (Pienkos, 2007), a need that results in large cultivation areas.

Open pond systems have the advantage of comparatively low capital and operational costs but the algae cultivation is subjected to contamination and to various variations, e.g., day-night, seasonal temperature, humidity, precipitations, etc. The evaporation of water also requires constant water supply and balancing the water composition, which includes the need for removal of salt accumulated due to the evaporation. The direct exposure to the environment implies that only species that can grow in non-sterile conditions can be used and even then, the cultivation will face contamination problems from local species. After many years of research, researchers have found only a handful of algae strains fulfilling the requirements for cultivation

in an open system. Yet, keeping specific, selected algal strain dominant in open ponds remains a major challenge.

Although a high water recycle rate is a key consideration in the design of the plant, large amounts of extra water are necessary. Assuming an average evaporation rate of 10%, *i.e.*, approximately 1 cm of the depth of the pond per unit area, the extra water requirements are about 15 million m³ per year for a 400 ha open pond system algae plant. Thus, having access to a large amount of cheap water and a water infrastructure is key for the economic viability of the system. In this report, water supply and distribution based on Weissman and Goebel (1987) and Benemann and Oswald (1996) is considered. These systems assume that brackish water is used and that even though it is free, it has to be drilled for and pumped up to the surface, which add to the cost.

An alternative to open ponds is a closed, tubular system, *i.e.*, photobioreactors, that is, transparent containers in which algae are cultivated. While photobioreactors provide controlled conditions that apart from maintaining the expected productivities also ensure a better utilization of the resources, like nutrients and water, their capital costs are higher; estimates are in the order of \$(2004) 100/m², about one order of magnitude higher compared to open ponds (Huntley and Redalje, 2006, van Harmelen and Oonk, 2006). According to Huntley and Redalje (2006), photobioreactor technology is still in the prototype stage but significant technological advances can be expected by the time the production of fuel from algae occurs at large scale (see for example Fahrendorf (2008) and Willson (2008)). However, their capital cost will always remain higher than those of open ponds. Thus, their ability to keep the species away from contamination and to maintain the conditions needed for optimum yields would become key in the decision making process.

Huntley and Redalje (2006) present a coupled cultivation system trying to combine the advantages of open and closed systems, while avoiding their disadvantages. The photobioreactors provide a continuous supply of culture grown in a controlled atmosphere to the open ponds. Once in the ponds, the culture is exposed to nitrogen starvation, which triggers a rapid lipid accumulation allowing a short residence time in the open part of the system and hence, reduces the risk of contamination. This, in turn, implies that a large number of strains can be cultivated.

The exact composition of the algae depends on the strain, but the three main components of all algal biomass are carbohydrates, proteins and lipids. To achieve high productivities, large amounts of the constituents of each of these components have to be supplied to the algae. These basic constituents are carbon, hydrogen, oxygen and, to a lesser percentage, nitrogen and phosphorus.

Currently, the average atmospheric concentration of CO₂ is approximately 385 parts per million by volume. Under such conditions the achievable algae growth rate is about 0.2 g/m²/day, which is far below the desired productivities of 30-50 g/m²/day (Putt, 2007). Thus, in order to achieve the high productivities needed to make algae production economically viable, additional CO₂ has to be fed to the algae. This extra CO₂ requirement

represents a crucial difference with respect to terrestrial biomass crops, a condition that has to be taken into account when considering lifecycle CO₂ emission implications of algae-based fuels.

Among the wide range of carbon sources, flue gases from the combustion of fossil fuels are most practical. Typical coal-fired power plants emit flue gas from their stacks containing up to 15 percent CO₂ per unit volume. However, the presence of other gases like nitrogen oxides (NO_x) and sulphur oxides (SO_x) implies that a cleaning of the flue gas would be necessary before it is injected into the ponds to avoid polluting the algae cultivation.

If the source of CO₂ is far from the algae plant, the cleaned gas should be compressed before its transportation. In this case, a high purity CO₂ would be desirable in order to optimize the transportation process. As an alternative to pure CO₂, flue gases cleaned of NO_x and SO_x can be used to fertilize the algae. However, in this later case, the cost of transporting the flue gas would be larger given its 6 to 7 times larger volume that has to be handled for the same amount of CO₂ (the CO₂ concentration is about 90% in the case of "pure" CO₂ but only 12-13% in case of the flue gas). The disadvantage of the use of flue gas compared to pure CO₂ increases with distance from the algae plant. Therefore, there will be a threshold distance that favors the economics of either approach. In this report it is considered that the use of flue gas is the option when the source of CO₂ is close to the algae plant, with purified CO₂ being considered for longer distances.

In addition to CO₂ and water, algae also require nutrients like nitrogen to build up the constituent proteins. While type and exact amount of nutrients depend on the specific composition of algae, nitrogen and phosphorus are two of the most common constituents for the algae strain under consideration (Benemann, 2003). Thus, algae have been used for the treatment of wastewater. In this report, the cost estimate presented in Weissman and Goebel (1987) is used.

3.2 Harvesting and oil extraction

Developing a low-cost harvesting process is still one of the most significant technological challenges of the entire algae fuel production system. A particular challenge is the small size of the algae and the associated difficulty of filtration. The basic harvesting approach involves an initial dewatering of the algae-water mixture and a subsequent centrifugation to eliminate the remaining water. The main disadvantage of the method is that large centrifuges are required due to the high level of water still in the mixture after the dewatering. In order to improve this process, a flocculation step has been suggested to be introduced before the dewatering in order to significantly reduce the amount of water that reaches the centrifugation step. However, this approach requires some specific characteristics from the algal strain, e.g., the ability to bio/auto flocculate, which allows the algae to form flocs (which are easier to harvest) under the presence of specific microbes or environments, and thus constrains the number of the algal strains that are suitable as a fuel feedstock. Because of the required high productivity from

an algae plant, the harvesting process will have to be carried out daily, as overcrowding would inhibit productivity.

Although much research is devoted to cost-effective harvesting techniques, these processes still need to be tested on the large scales required.

The extraction of the algal oil also represents an important challenge in the production of oil from microalgae. Many methods are available at laboratory scale like crushing, the use of chemical solvents or ultrasound. However, scaling these processes up to the required commercial level and keeping the costs low are challenging tasks.

For the case study presented below, the work done by Benemann and Oswald (1996) has been followed. The authors used polymers and a dissolved air flotation system to enhance the flocculation and to reduce the amount of water to approximately half of the conventional first step harvesting. This concentrated algal biomass is converted to an oil emulsion to increase the capacity to extract the oil before entering the centrifuge. According to the authors, the harvesting and extraction of the algal oil can be carried out with this technique.

3.3 Fuel Processing

The three main components of the algal biomass are carbohydrates, proteins and lipids. The lipid constituents represent the "natural" feedstock for fuel manufacturing but the energy contained in the other components also represents an important source of energy.

In the study presented here, the lipid component is extracted from the algae to form an algal oil that is further processed to biofuel. A typical microalgal lipid molecule is being considered as a triglyceride of a polyunsaturated 18-carbon fatty acid, $C_{57}H_{62}O_6$ (Feinberg and Karpuk, 1990). This formula corresponds to the glycerol compound esterified with three fatty acids. The amount of energy needed to convert the algal oil into to a biofuel together with the associated emissions has been estimated on the basis of the conversion from soy oil to a renewable diesel shown by Wong (2008), which is based on a hydrotreating process (Holmgren, 2008). The cost of processing the algal oil into biodiesel has been obtained from Saas et al. (2005) and ranges from \$(2005) 0.3 to \$(2005) 1 per gallon of algal oil. This range agrees with that suggested by Benemann and Oswald (1996). According to Marinangeli *et al.* (2005), the overall cost of biodiesel production could be nearly twice that of the hydrotreated diesel. In this report, the minimum and the maximum values of the latter have been used as an estimate, i.e., from \$(2005) 0.15 to \$(2005) 1 per gallon of algal oil. The remainder biomass is sent to the anaerobic digester for the conversion into biogas and the recycling of nutrients.

3.4 Anaerobic digester

Anaerobic digestion (AD), that is the breakdown of organic matter by bacteria in the absence of oxygen, converts part of the organic carbon contained in the remaining biomass into a biogas, which contains CH_4 and CO_2 . The amount of biogas and residues of the process (as well as their composition)

depends on the starting feedstock. Vergara-Fernandez *et al.* (2007) show that a biogas with a methane concentration of 50 to 65 percent can be generated from marine algae. The solid residue from the process, digestate, can be used as an organic fertilizer. The biogas from an anaerobic digester can be used to generate heat and/or electricity and used onsite to assist some of the processes that require thermal energy, e.g., for drying the algae.

For the case study presented in section 3.5, a covered anaerobic lagoon has been considered given that it has the most favourable biogas production cost per unit of heat energy. The input feedstock to the anaerobic digester corresponds to the remainder biomass once the lipid components have been extracted. The digestion process is characterised by Table 4 and it has been obtained from Weissman and Goebel (1987), where C, N and P refer to carbon, nitrogen and phosphorus respectively, which are the nutrients that are considered in this report. The percentage of each of the components in the different phases refers to the biomass input to the anaerobic digester.

Table 4: Characterization of the anaerobic digestion

	% of total C	% of total N	% of total P
Gas	65	0	0
Liquid	18	75	25
Digestate	17	25	50

Of the gas phase indicated, 60% of the carbon is considered to become methane and the remaining 40% is in the form of CO₂ (39% and 36% of the total carbon at the inlet of the digester, respectively). The design parameters and economics of the anaerobic digester are given in Weissman and Goebel (1987).

3.5 Case Study

For the case study, a 400 ha algae plant will be analyzed. The algae are grown in open shallow raceway ponds, mixed with paddle wheels, harvested by flocculation and centrifugation, which overlaps with the oil extraction process and the further processing to biofuel. The remaining biomass is sent to an anaerobic digester to produce methane and electricity to satisfy in-plant energy demand and to enhance the recycling of nutrients. The diagram of the system and its boundaries are shown in Figure 2. The fuel cycle considered here includes the capture (and conditioning) of CO₂ that the algae require from the power plants and its transport and distribution to and within the algae plant. This analysis is mainly based on existing literature.

The supply of both pure CO₂ and flue gas has been considered in the analysis. Unless otherwise stated, the results presented in this report, correspond to a growth rate of 30 g/m²/day and 50% lipid content. This value has been used as the baseline in several techno-economic analyses carried out in the past (Weissman and Goebel, 1987 and Benemann and Oswald, 1996). Note that this productivity is *not* representative of today's level of technology in open ponds and according to Benemann (2008) the oil yield obtained by this productivity can only be achieved through long-term

R&D efforts. A representative yield of *current* productivities in open ponds would be about 10 g/m²/day and 15% lipid content (Sheehan *et al.*, 1998). This case yields about one order of magnitude less fuel than the value assumed in this report and is similar to the best terrestrial crop, the oil palm. The sensitivity tests using the current productivities will be discussed below.

Mass balance

The mass flows of some of the components for the 400 ha open ponds system for the case of pure CO₂ feed are shown in Figure 2.⁵ The algae feedstocks produced by the 400 ha open ponds system are sufficient to produce 18,185 tonnes of jet fuel, 1,026 tonnes of propane, and 1,836 tonnes of solid digestate per year.⁶ Under the assumptions considered in this study, the production of one ton of bio-jet fuel requires about 4 tons of CO₂ from the power plant, 0.03 tons of nitrogen and 820 tons of water.

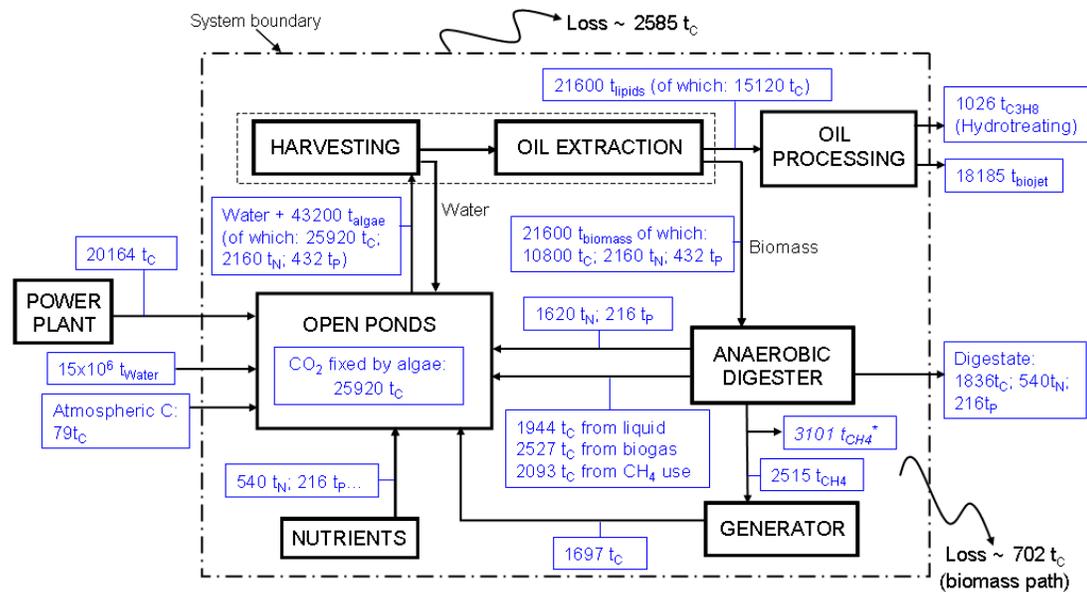


Figure 2: Annual Mass flows on a 400 ha open pond system assuming pure CO₂ feed. The algae growth rate is assumed to 30 g/m²/day and the lipid content is 50 percent

In Table 5, the basic assumptions to calculate the values shown in Figure 2 are shown. The various losses indicated at the systems boundary in Figure 2 will be discussed in the following sections.

Table 5: Main assumptions of the system

Cultivation season (days/year)	360
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⁵ The mass flows of hydrogen and oxygen are not essential for the fuel cycle analysis carried out in this report and therefore are not considered. They would only be necessary if, for example, the remainder biomass from the oil extraction process followed another route like the fermentation to produce ethanol.

⁶ For the conversion of the lipids to algal oil yield, a density of 0.864 kg/litre has been assumed (Miao and Wu, 2006). A conversion factor from the algal oil to renewable diesel of 0.842 has been considered (Wong, 2008).

Size of the open ponds algae plant (ha)	400
Growth rate (g/m ² /day)	30
Algae characterization (%)	
Carbon in the dry algae	60
Nitrogen in the dry algae	5
Phosphorus in the dry algae	1
Lipids in the algae	50
Carbon in the lipids	70
Biomass converted to biogas	65
CH ₄ in the biogas	60
CO ₂ in the biogas	40
Atmospheric CO ₂ fixed (g/m ² /day)	0.2

Energy use

The energy consumed and produced from the different processes of the system is shown in Table 6.

Table 6: Annual energy breakdown on a 400ha open pond system

	Without CCS		With CCS	
	Pure CO ₂	Flue Gas	Pure CO ₂	Flue Gas
Algae feed and cultivation				
Electricity (10 ⁶ kWh)				
Harvesting and oil extraction ^a	3.1	3.1	3.1	3.1
Miscellaneous ^c	9.8	9.8	9.8	9.8
CO ₂ upgrading and supply ^d	34.0	8.7	8.9	6.0
Fuels (TJ)				
Nutrients manufacturing ^b	32.4	32.4	32.4	32.4
Oil processing ^e				
Electricity (10 ⁶ kWh)	0.5	0.5	0.5	0.5
Fuels (TJ)				
Hydrogen input (TJ)	70.5	70.5	70.5	70.5
Natural Gas input (TJ)	3.6	3.6	3.6	3.6
Algae plant outputs ^f				
Electricity (10 ⁶ kWh)	(-)14.8		(-)14.8	
Fuels (TJ)				
Methane	(-)153.5	(-)305.0	(-)153.5	(-)305.0
Synthetic jet fuel	(-)800.1	(-)800.1	(-)800.1	(-)800.1
Propane	(-)47.0	(-)47.0	(-)47.0	(-)47.0
Total Inputs				
Electricity (10 ⁶ kWh)	47.4	22.0	22.3	19.4
Total Outputs				
Electricity (10 ⁶ kWh)	(-)14.8		(-)14.8	
Synthetic Jet Fuel (TJ)	(-)828.3	(-)919.2	(-)828.3	(-)919.2
Fuel Cycle Energy Use, MJ/MJ_{Product}	0.44	0.27	0.10	0.17

Notes:

^a Values calculated from data reported in Benemann and Oswald (1996).

^b Values calculated from data reported in Farrell *et al.* (2006).

^c This term includes the energy required for the mixing system, water supply, anaerobic digester, *etc.* Apart from the energy requirements by the anaerobic digester, which are based

on Hilborn (2007), energy use by the remaining plant components is based on Benemann and Oswald (1996).

^d Energy demand for CO₂ separation depends on the type of process, i.e., absorption, membranes, cryogenic separation, or other processes. The value associated to these processes could vary between 0.09 and 1 kWh/kgCO₂ if the entire range of possibilities were considered. This range would then account for the different physical and chemical conditions of the input gas stream and the purity of the resulting gas amongst other parameters. In this report and for the case of pure CO₂ feed, a value of 0.34 kWh/kgCO₂ is assumed as a baseline that corresponds to that reported by Gottlicher and Pruschek (1997) for the CO₂ recovery from flue gas by an absorption process. This process guarantees high purity of the recovery gas, which is consistent with the needs of low transportation cost and a high removal rate. A value of 0.12 kWh/kgCO₂ is used for the compression process (Gottlicher and Pruschek, 1997). In the flue gas case, a value of 0.033 kWh/kgCO₂ has been considered to account for CO₂ upgrade (Kadam, 2001) and a value of 0.075 kWh/kgCO₂ has been used for the distribution of the feed within the plant (Benemann and Oswald, 1996). For the case of a power plant with a carbon and sequestration unit, only the factor corresponding to the conditioning for transportation of the CO₂ is applied.

^e Values calculated from data reported in Wong (2008).

^f Values calculated from data reported in Benemann and Oswald (1996) and Wong (2008)

The energy required for the manufacturing of the nutrients (nitrogen and phosphorus) represents about 10% of the methane obtained from the anaerobic digester. The amount of energy required for the production of the nutrients is about 56 MJ/kg_N for nitrogen and 10 MJ/kg_P for phosphorus (Farrell *et al*, 2006). The manufacture of nitrogen dominates the total energy input, even though the percentage of this nutrient in the dry algae assumed for this example, 5 percent, is near the minimum possible content of nitrogen in conventional microalgae, i.e., about 4 percent according to Benemann (2003).⁷ This highlights the importance of using wastewater with high nutrient content, *i.e.*, dissolved fertilizers, in order to save manufacturing energy. Alternatively to the fuel production process, the algae plant can be considered as an efficient method of recovering fertilizers in wastewaters.

The different values in electricity consumption for CO₂ upgrading and supply in the scenario without a CCS unit for the cases of the pure CO₂ and the flue gas are due to different processes, i.e., (i) the upgrading of the CO₂, which is about one order of magnitude higher for the case of the pure CO₂ (see note d), and (ii) the compression, transportation, and supply of the CO₂ to the algae, which is approximately 60 percent higher for the case of the pure CO₂ (see note d). Given that this gas is supplied to the algae plant at a high pressure, it does not need any conditioning for its distribution within the plant. However, the supply of the flue gas requires more power owing to the 6-7 larger mass flow of gas (at a lower pressure) that has to be handled within the plant for the same amount of CO₂. For the case in which the power plant has a CCS unit, it is assumed that the CO₂ is already separated and therefore, only the contribution of the term corresponding to the conditioning for transportation and distribution of the CO₂ has to be considered.

The outputs from the algae plant are assumed to be used to satisfy energy demands within the plant. Methane from the anaerobic digester is

⁷ According to Benemann (2003), the percentages of nitrogen and phosphorus of the dry algae normally vary from 4 to 12 percent and from 0.3 to 1.2 percent, respectively

used to produce hydrogen for the processing of the algal oil and to provide for the energy for manufacturing the fertilizers. In the case of the flue gas feed, the remaining methane is then converted to a synthetic liquid fuel. The efficiency of the production of hydrogen from methane in small reformers is about 60 percent (Weiss *et al.*, 2000). In the pure CO₂ case, the remaining methane is burned in a generator to produce electricity which can be used inside the plant for the processes requiring power. Any electricity surplus can be then sold the grid. The efficiency of the generation of electricity from the methane is assumed to be 32 percent (Benemann and Oswald, 1996).

For the calculation of the fuel-cycle energy use, the different inputs and outputs have to be brought to a comparable quantity. Thus, electricity is converted to primary energy using a 32 percent thermal efficiency. Any surplus methane and propane are converted to a synthetic liquid fuel with an efficiency of 60 percent, which is being added to the produced synthetic jet fuel. These numbers are presented as a range in Table 3. The fuel cycle energy use then results in 0.10 – 0.44 MJ per MJ of jet fuel, depending on whether the coal power plant that provides the CO₂ feed operates with a CCS system (lower value) or not (higher value).

CO₂ balance

Figure 3 shows the systems boundary underlying the CO₂ balance of the algae fuel production system. The values presented in the figure have been calculated considering the assumptions given in Table 5 and in the 'Energy use' section.

Algae consist of roughly 60% of carbon by weight and thus, growing 1 kg of algae requires 0.6 kg of carbon or 2.2 kg of CO₂. Only a small amount of the CO₂ that the algae need is absorbed from the atmosphere. This value is about 0.7% of what the algae fix for the productivity shown in Figure 3. Also in this Figure, the amount of CO₂ recycled to the ponds from the anaerobic digester and the generator are presented. These values are calculated with the mass flows shown in Figure 2 and the characteristics of the digestion process presented on Table 4. In order to calculate the CO₂-eq emissions associated with the supply of nutrients, it has been assumed that 7 kgCO₂-eq and 1.6 kgCO₂-eq are emitted per kilogram of nitrogen and phosphorus required from the plant (Farrell *et al.*, 2006). An equivalent of about 10 percent of the CO₂ that the algae fix is lost due to the inefficiencies in the transportation, distribution and transfer systems. Similar numbers have been suggested in Benemann *et al.* (1982), Weissman and Goebel (1987) and Benemann and Oswald (1996). These losses are considered for the calculation of the CO₂ needed from the power plant. An additional CO₂ loss corresponding to the biomass path has been added to the balance. This value is based on a gas recycling rate of 90% (Weissman and Goebel, 1987), i.e., a 10% loss.

Given the large amount of CO₂ necessary for the high productivities required, the carbon contained in the carbohydrate and proteins left from the oil extraction process ought to be recycled as algae feed. Part of the methane obtained from the anaerobic digester is used for the production of hydrogen. The CO₂ resulting from this step is also recycled to the ponds. In

the case of the flue gas, the remaining methane is converted to synthetic liquid fuel involving no further recycling. However, in case of pure CO₂, the remaining methane can still be burned in the generator, from where more CO₂ can be recycled to the ponds. This implies that, with the assumptions considered in this study, the amount of CO₂ recycled is smaller when a flue gas feed is used.

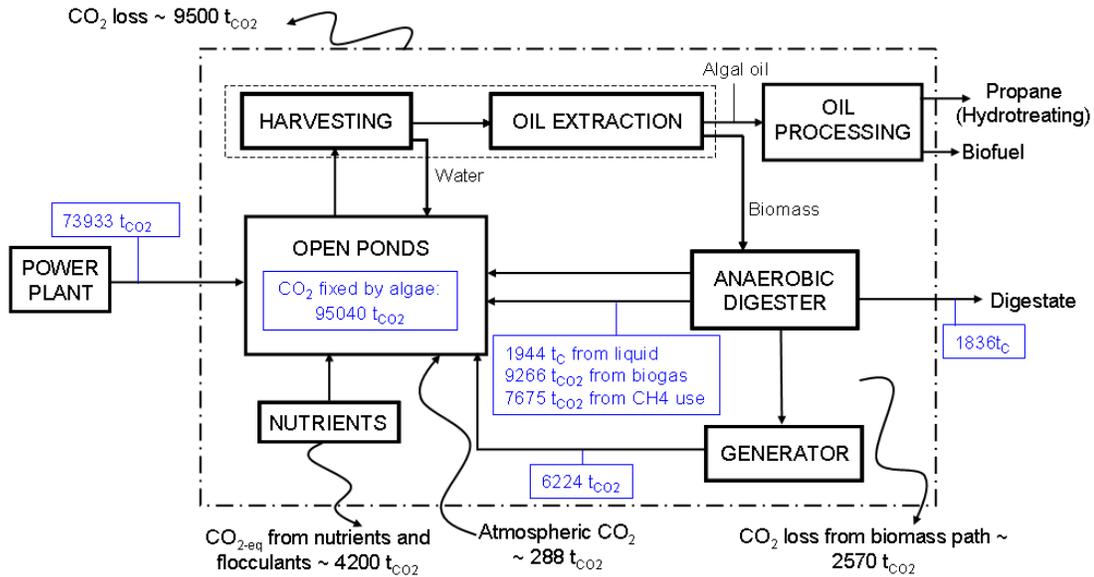


Figure 3: Annual CO₂ balance throughout the system with pure CO₂ feed

The algae plant is related to the power plant through the CO₂ required to feed the algae and the electricity to power the algae plant. In the scenario, in which the coal power plant does not have a CCS unit, the different relative amounts of CO₂ and electricity acquired from the power plant would modify the CO₂ intensity of the electricity leaving the plant that is fed into the electrical grid. This is because the algae plant's demand for CO₂ is larger than its demand for electricity. In order to maintain the CO₂ intensity of the electricity produced by the power plant, it is assumed that the algae plant acquires more electricity than it needs such that the power plant characteristics remain unaffected by the algae plant. Following this approach, any change in the CO₂ balance is fully attributed to the algae system.

Based on Figure 3, it can be seen that the total amount of CO₂ that will be released to the atmosphere is the result of several terms. Firstly, a term corresponding to the release of CO₂ that includes the CO₂ that the algae plant obtains from the power plant plus the CO₂ due to the manufacturing of the nutrients and due to the conversion of the fuel gases into synthetic fuel (the latter, small term is not shown in the figure). Secondly, a 'credit' term corresponding to the CO₂ absorbed from the atmosphere and the equivalent CO₂ that leaves the system boundary as solid carbon within the digestate. The latter component depends on where the boundary of the system is set.

In addition, the CO₂ avoided for providing zero-carbon electricity has also to be taken into consideration and credited to the algae system. This

term consists of the amount of electricity associated with the CO₂ acquired by the algae plant for maintaining the electricity generation characteristics at the power plant plus any surplus electricity produced at the algae plant, minus the electricity consumed by the algae system. The CO₂ equivalent emissions associated with the surplus zero-carbon electricity term should be then credited to the algae. These values together with the resulting lifecycle GHG emissions are shown in Table 7.

The results in Table 7 show that in the case of a coal power plant with uncontrolled CO₂ emissions, microalgae-based fuels can provide a low carbon fuel. The lifecycle GHG emissions of microalgae-based fuels would only account for 20 to 40 percent of the petroleum-derived jet fuel. However, if the coal power plant is equipped with CCS, as it may increasingly be the case in a carbon-constrained economy, the lifecycle CO₂ emissions would be similar. This is because for this case, and following the argument above, no credit should be given to the algae system given that there is no 'free CO₂ electricity' associated to the CO₂ used by the algae plant.

Table 7: Annual CO₂ balance throughout the system (t_{CO2})

	Without CCS		With CCS	
	Pure CO ₂	Flue Gas	Pure CO ₂	Flue Gas
CO ₂ from power plant	74000	80200	74000	80200
CO ₂ -eq emissions – nutrient + synt. fuel processing	4700	5500	4700	5500
Atmospheric CO ₂ absorbed	(-)300	(-)300	(-)300	(-)300
CO ₂ -eq in solid Carbon within digestate	(-)6700	(-)6700	(-)6700	(-)6700
GHG emissions - released gCO ₂ -equivalent/MJ _{Product}	86	86	86	86
GHG emissions - credited gCO ₂ -equivalent/MJ _{Product}	(-)55	(-)66	0	0
Life-cycle GHG emissions, gCO₂-equivalent/MJ_{Product}	31	20	86	86

Notes:

The losses are due to the inefficiencies in the transportation, distribution, transfer systems and biomass path.

An emission factor of 0.88 kg CO₂/kWh, representative of a coal power plant, has been considered (www.berr.gov.uk) for the scenario without CCS unit.

Economics

The economic analysis has been performed following the work of Benemann *et al.* (1982), Weissman and Goebel (1987), and Benemann and Oswald (1996). The cost of electricity has been adjusted to the 2005 value of \$0.057/kWh⁸ and the cost of the pure CO₂ has been taken as \$50/t_{CO2} (Benemann and Oswald, 1996).⁹ For the flue gas case, it is assumed that the CO₂ is for free, given that its cost would be small in comparison with the case of the pure CO₂. For simplicity, it is considered that the methane and

⁸ www.eia.doe.gov

⁹ If the costs for separating, compressing and transporting the CO₂ was calculated as a function of the amount of CO₂ needed by the algae plant (throughput), the cost of CO₂ would be about \$90/t_{CO2} (Anada *et al.*, 1983; Feinberg and Karpuk, 1990). These values apply to the case at which only the CO₂ needed for the algae plant is treated and transported. However, it is assumed that the CO₂ infrastructure is shared with other plants or CO₂ applications and the value suggested by Benemann and Oswald (1996) has been used in this study. This value is therefore an optimistic estimation of the price of CO₂.

propane, that in previous sections have been accounted as a FT synthetic fuel for the energy and the CO₂ balances, are sold as gaseous fuels. The sales price of methane is about \$2.37/GJ (Newenham, 2002) and that of propane is about \$0.95 per gallon⁶. For the production of hydrogen from methane, a conversion efficiency of 0.6 has been used (Williams *et al.*, 1994).

Figure 4 shows the costs associated with the production of bio-jet fuel from the 400 ha open ponds algae plant for the case of pure CO₂ feed and flue gas feed. For simplicity, the cases shown in Figure 4 correspond to the scenario without CCS unit. The cost per barrel of biojet fuel is about \$(2005) 125/bbl and \$(2005) 95/bbl for the cases of pure CO₂ and flue gas respectively. These values result once the credits for the fuel from the biomass and the propane have been accounted for¹⁰. For comparison, the price of petroleum-derived kerosene was about \$68/bbl⁶ and \$120/bbl⁶, in 2005 and 2008 respectively. The 2008 price is about the same value obtained for the pure CO₂ feed with the productivity considered in this study. However, it is worth highlighting that the values presented in Figure 4 have been obtained considering an optimistic CO₂ price and a highly integrated algae plant with different processes taking place, *i.e.*, anaerobic digestion, generation of electricity, processing of the algal fuel *etc.* In addition, an optimistic value of the productivity has been considered. This integration is essential to make the algae system economically viable.

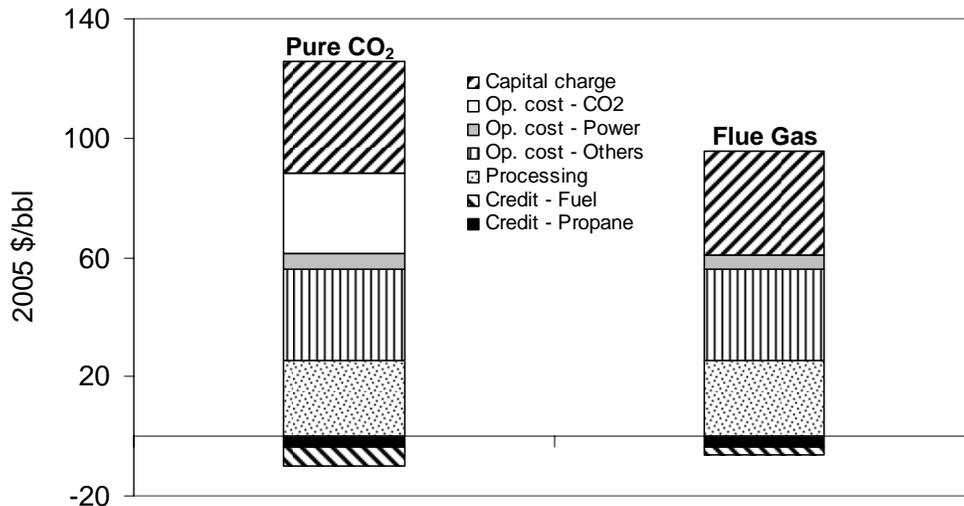


Figure 4: Cost per barrel of biofuel from microalgae assuming no CCS unit. The algae growth rate is assumed to be 30 g/m²/day and the lipid content is 50 percent.

When comparing the costs of pure CO₂ feed and flue gas feed, the main difference is the cost of CO₂, accounting for approximately 43% of the operational costs in the pure CO₂ feed case.

Equivalent calculations have been performed assuming a productivity representative of today's level of technology. In this case, not shown here, the cost per barrel was about \$700/bbl, highlighting the need of the very high

¹⁰ The digestate, a valuable byproduct of the system has not been considered in this analysis.

productivities presented in this report in order to make the system economically feasible.

Carbon credits can also be included in order to enhance the economic feasibility of the system. To calculate the credited CO₂, the life-cycle GHG emissions of the biojet from algae (see Table 7) should be compared with the life-cycle GHG emissions associated to the baseline petroleum derived jet fuel (see Table 3). The credited CO₂ is about 0.28 and 0.35 tonnes of CO₂ per barrel for the pure CO₂ and the flue gas feed respectively. Assuming the CO₂ is credited at \$(2005) 30/ton CO₂, the cost of the fuel presented in Figure 4 will decrease by about \$(2005) 8-11/bbl. CO₂ abatement is therefore not an economic driver.

Land Requirement

The global consumption of jet fuel (commercial and military) was about 720 million litres per day during 2003 (Chevron, 2006 (2)). The land required to supply the later amount of fuel has been estimated using the fuel productivities considered and it is shown in Figure 5. Using current productivities (10g/m²/d and 15 percent lipids, in light blue), an area equivalent to the peninsular area of Spain or 1.8 times the state of Colorado would be needed. The light blue code is also equivalent to the area that the best terrestrial crop (palm oil) would require to produce the same amount of fuel. At the moment, the yield of the best terrestrial crop is larger than the yield of the realistic productivity of algae. The land requirement decreases when considering the higher productivities considered in this study (30g/m²/d and 50 percent lipids, in maroon) and become about 10% of peninsular Spain or 18% of Colorado. Considering the maximum possible productivity, which is about 50g/m²/d and a 50 percent lipids content (shown in dark blue in the Figure), would imply a land requirement of 6 percent or 11 percent the area of peninsular Spain or of the state of Colorado respectively. A 7% of the areas shown in Figure 5 would be needed to fuel the 2007 demand of the UK commercial aircraft fleet (about 50 million litres per day).

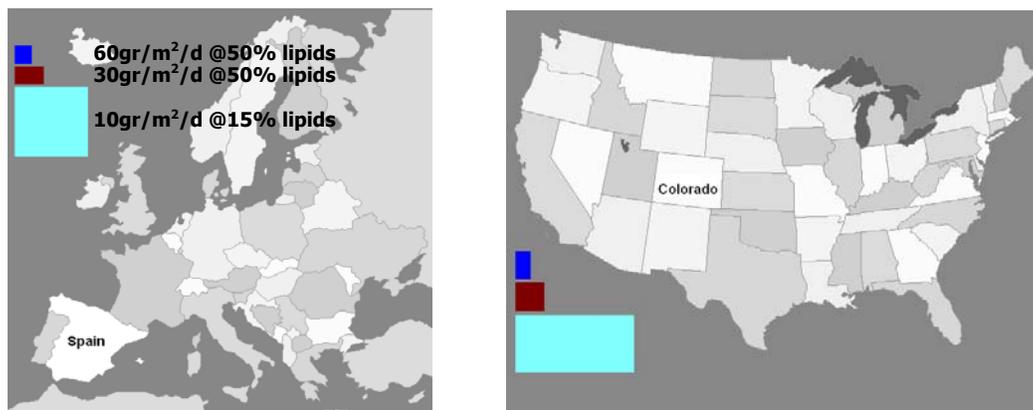


Figure 5: Land requirements to supply the world consumption of jet fuel during 2003

Acknowledgements

This project was funded by the Omega consortium (www.omega.mmu.ac.uk). The Aviation Integrated Modelling project is funded by EPSRC and NERC.

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Appendix 1: Recent test flights with alternative fuels

Even though the test flights with alternative fuels have only spanned over one year, a change in the biofuel trend can be seen that reflects the new developments on the research for alternative aviation fuels, i.e., from the initial test with a Fischer-Tropsch fuel derived from gas to the hydrotreated vegetable oils. A summary of the tests flights carried out to date is listed below.

1st February 2008: An Airbus A380 with a blend of fuel processed from gas (gas to liquid –GTL) mixed with regular fuel. The blend was used in one of the four Rolls-Royce Trent 900 engines powering the aircraft.

24th February 2008: A Boeing 747-400 from Virgin Atlantic with a blend in one of the four CF6 engines. The blend was 20% a biofuel derived from coconut and babassu and 80% conventional oil.

6th January 2009: A Boeing 747-400 from Air New Zealand with a 50% blend in one of the four Rolls-Royce RB211 engines powering the aircraft. The blend was 50% conventional Jet A and 50% Jatropa.

9th January 2009: A Boeing 737-800 from Continental Airlines with a 50% blend in one of the two CFM56-7B engines powering the aircraft. The blend was 50% conventional Jet A, 47.5% Jatropa and 2.5% of algae.

30th January 2009: A Boeing 747-300 from Japan Airlines with a 50% blend in one of the four Pratt & Whitney JT90 engines powering the aircraft. The blend was 50% conventional Jet A, 42% Camelina nearly 8% of Jatropa and under 1% of algae.

As it was discussed in section 2.1, given the limitation of the high freezing point of the FAMEs, only blends including a low percentage of them (less than 20%) are suitable as drop-in fuels. Any blend with a higher percentage might be a hydrotreated vegetable oil. The research on new feedstocks is based on the necessity to overcome the drawbacks of the most commonly known ones, like the food-versus-fuel competition. This has resulted in the use of relatively unknown plants in the tests flights shown above, like jatropa and camelina. An estimation of the life-cycle GHG emissions for the jatropa and the camelina oil can be calculated as follows:

- Jatropa oil: According to Fulton (2007), the jatropa oil is in the same category as the palm oil when it comes to GHG reduction impacts versus petroleum fuel, i.e., both of them present a moderate/high GHG reduction impact (unlike the oil seeds like rape or soy which only have a moderate GHG reduction). The advantage of the jatropa feedstock is that contains non-edible oils and that could grow in non-arable lands and, hence, its cultivation does not compete with food. Its productivity

however is about 40-45% that one of the palm oil (Holmgren, 2007). Although the productivity of jatropha is about 40-45% of that of the palm oil, it will be assumed here that a similar amount of energy is needed for a given output. From a life cycle GHG emission point of view, the use of jatropha with a hydrotreating process could be similar to using palm with the same process. The value of the later has been obtained from Wong, (2008), and it is about 26.2 gCO₂-eq/MJ_{Product}. Accounting for the lower productivity of jatropha versus the palm oil, the life cycle GHG emission for the jatropha could be increased to a range of (25-35) gCO₂-eq/MJ_{Product}.

- Camelina oil: The camelina is a distant relative of rapeseed which can grow on marginal land. The productivity of the camelina is about 65 to 100 gallons of oil per acre¹¹. The soil fertility needs of camelina are likely similar to those of other crucifers with the same yield potential¹², although companies are using research to modify the seed, producing higher yields that require less fertilizer and water. Taking the later into consideration, a value of (40-50) gCO₂-eq/MJ_{Product} could be used as an initial approximation for the life cycle GHG emissions for the camelina oil.

The life-cycle GHG emissions of various petroleum and alternative fuel blends¹³ are presented in Figure A1 along with those from purely petroleum-derived jet fuel. All blends with hydrotreated vegetable oils present a larger GHG emission reduction in comparison with the GTL or FAME blends. However, the lower life-cycle GHG emissions can be achieved through cellulosic biomass-based synthetic jet fuel (BTL). Assuming a 50% blend, the life-cycle GHG emissions are about 50 gCO₂-eq/MJ_{Product}, i.e., slightly more than half those of pure petroleum-derived jet fuel. This value is dominated by the petroleum-derived jet fuel contained in the blend and consequently it could be further decreased for higher blends of the BTL. This value could also be decrease if a carbon capture and sequestration unit is used at the synthetic fuel production plant and if biomass with lower associated emissions is used as a feedstock.

¹¹ <http://cleantech.com/news/4114/japan-air-completes-camelina-biodie>

¹² www.hort.purdue.edu/newcrop/proceedings1993/v2-314.html#Fertilizer%20and%20Water%20Needs,%20Insects%20and%20Diseases

¹³ In order to calculate the life-cycle GHG emissions for the flight, a weighted value considering the conventional petroleum fuel used by the rest of the engines would have to be calculated.

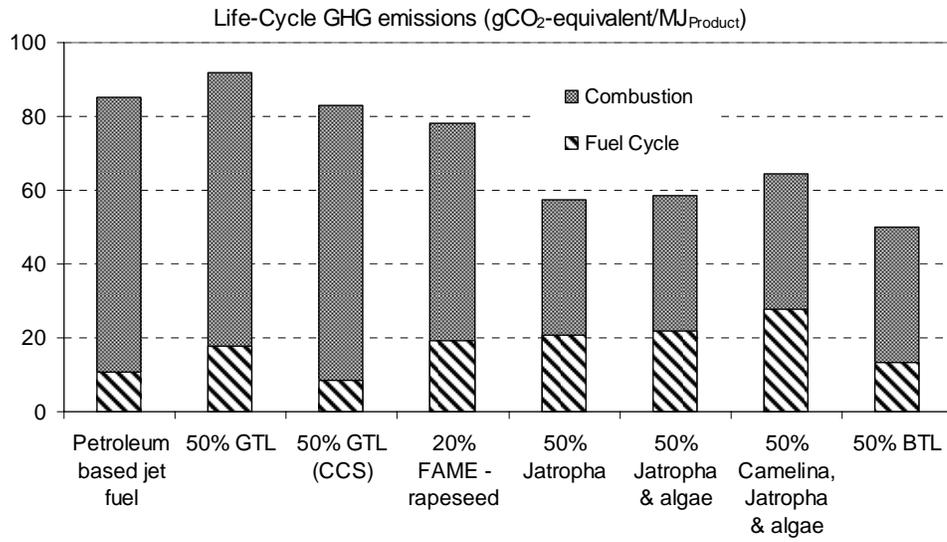


Figure A1: Life-cycle GHG emissions of different blends