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Algae as a source of fuel for the Dutch aviation sector

A feasibility study

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In de Luchtvaartnota, die begin 2011 door de Tweede Kamer is vastgesteld, wordt het belang van een concurrerende en duurzame luchtvaart ten behoeve van een sterke BV Nederland benadrukt. In het kader van een duurzame ontwikkeling van de luchtvaart wordt onder andere de nadruk gelegd op vermindering van de uitstoot van CO_2. Daarbinnen is de ontwikkeling en toepassing van alternatieve duurzame brandstoffen een belangrijke pijler, waarlangs invulling gegeven kan worden aan de (inter-)nationale doelstellingen voor de reductie van de uitstoot van CO_2 emissies. Binnen het geschetste kader heeft het Ministerie van Infrastructuur en Milieu – Directoraat-Generaal Luchtvaart en Maritieme Zaken Deltares verzocht een eerste verkenning te doen van de (economische) haalbaarheid van de productie van algenkerosine voor de Nederlandse luchtvaart.

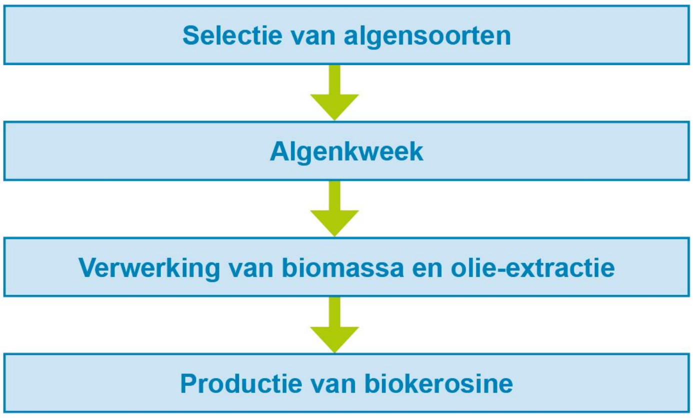
Dit rapport geeft een overzicht van beschikbare kennis en technologieën op het gebied van algenkerosineproductie, identificeert kennisleemtes en obstakels voor grootschalige commerciële toepassing, geeft inzicht in de huidige haalbaarheid van het toepassen van algenkerosineproductie voor de Nederlandse luchtvaartsector, en presenteert overwegingen over de toekomstige economische haalbaarheid van algenkerosine als brandstof.

Introductie
Op dit moment zijn de grootste problemen die ondervonden worden met alternatieve brandstoffen, zoals brandstof op basis van palmolie en jatrofa, dat voor de productie veel zoet water en vruchtbare grond voor landbouw nodig is, wat leidt tot competitie met voedselgewassen. Echter, microalgen worden gezien als een nieuwe bron van olie, met de potentie om deze problemen te ondervangen. Deze oliehoudende algen kunnen namelijk in zout water gekweekt worden en bovendien op locaties die ongeschikt zijn voor landbouw.

Naar aanleiding van de prijsstijging van olie in de jaren ’70 is in de Verenigde Staten een onderzoeksprogramma opgestart om te kijken in hoeverre algen geschikt zijn als bron voor brandstof. De daling van de olieprijs in de jaren ’90 had tot gevolg dat dit onderzoeksprogramma werd stopgezet. De nieuwe piek in olieprijzen in 2008 zorgde voor hernieuwde interesse in algenolie. Wereldwijd zijn onderzoeksprogramma’s opgezet om de verschillende processtappen voor de productie van algenbrandstof te optimaliseren.

State of the art
De vier onderdelen van het productieproces van algenkerosine zijn:
- **algensoortselectie**: welke soort kan het best gebruikt worden?
- **algenkweek**: welk kweeksysteem kan het best gebruikt worden?
- **algenverwerking**: hoe haal je de gekweekte algen uit het water en hoe haal je de olie uit de algen?
- **toepassing algenolie**: hoe kan algenolie omgezet worden tot kerosine (Figuur A)?

Algensoortselectie
Er zijn veel verschillende algensoorten met ieder een unieke combinatie van kenmerken. De ideale algensoort heeft een hoge olieconcentratie en een hoge productiviteit, lage nutriëntbehoeftes, hoge tolerantie voor temperatuurswisselingen en heeft een lage gevoeligheid voor de gevolgen van rondpompen van water. Er wordt veel onderzoek gedaan naar de optimale algensoort en algen worden ook genetisch gemodificeerd om de productiviteit te verbeteren, maar op dit moment is er nog geen ‘optimale’ algensoort geïdentificeerd die aan alle kenmerken voldoet.



Figuur A. Schematische weergave van het algenkerosine productieproces

Algenkweek
Er zijn verschillende kweeksystemen, waarvan wij de vier met de hoogste potentie in beschouwing hebben genomen:

1 open systemen, waarin algen in de buitenlucht gekweekt worden in een ondiepe laag water
2 ”tubular” fotobioreactoren (FBR), waar in een gesloten systeem van buizen algen worden gekweekt
3 “flat panel” fotobioreactoren, kweek in horizontaal geplaatste platen waar een dunne laag medium tussen zit
4 heterotrofe productie, algenkweek in het donker, waar suikers gebruikt worden als energiebron in plaats van licht.

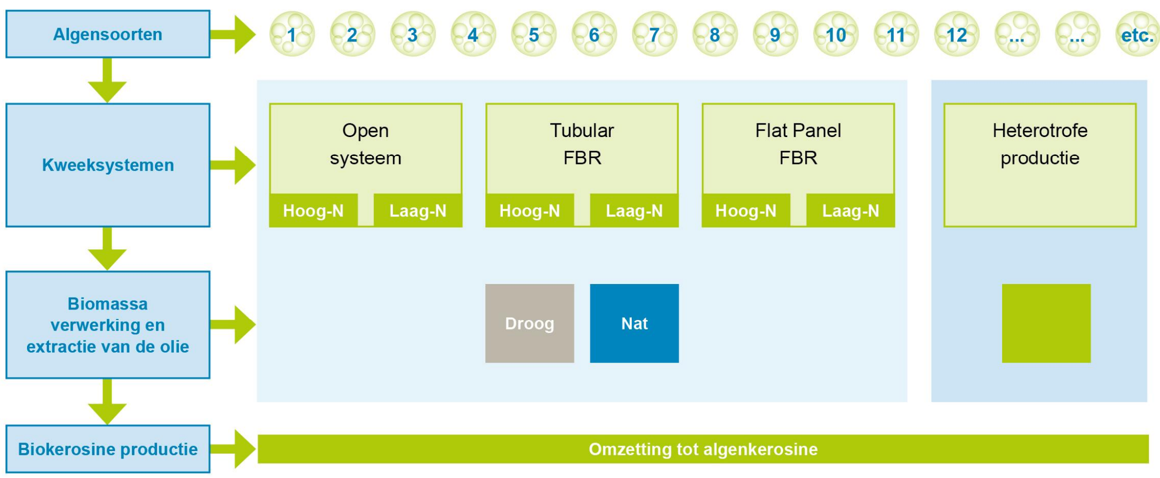
De verschillende kweeksystemen hebben elk voor- en nadelen. Zo is een open systeem het minst kostbaar, maar speelt besmetting een grote rol, waarbij de gewenste algensoort verdrongen kan worden door een ongewenste soort. In de gesloten systemen speelt dat nagenoeg niet mee, maar moeten nutriënten en CO_2 actief rondgepompt worden om de algen van voedingsstoffen te voorzien. Dit kost echter veel energie en zorgt voor stress voor de algen. Heterotofe productie levert de hoogste opbrengst per m^2, maar heeft suikers nodig als energiebron, wat ook erg kostbaar is.

Algenverwerking
Nadat algen gekweekt zijn, moet de algenbiomassa van het groeimedium gescheiden worden. Dit is een lastig proces waar veel energie voor nodig is. Vervolgens kan de olie uit de algen worden gehaald.

Er bestaan twee methoden om dit verwerkingsproces te doorlopen; de droge en de natte methode. Met de droge methode wordt het medium met algen eerst gefiltreerd, gecentrifugeerd en wordt de algenmassa met gebruik van warmte gedroogd alvorens de celwanden te doorbreken om de olie te extraheren. Met de natte methode wordt de olie uit de algen gehaald wanneer de algenmassa nog relatief nat is. Deze ‘natte’ methode bespaart energie (er is minder droging met behulp van warmte nodig), maar dit is op grote schaal nog niet mogelijk. Na olie-extractie kan de olie omgezet worden in biokerosine door middel van hydroprocessing.

Toepassing algenolie
Sinds juli 2011 is het toegestaan om in vliegtuigen een mix van 50% petroleum kerosine en 50% biobrandstof te gebruiken, zolang de brandstof aan internationale ASTM standaarden voldoet. Biokerosine uit algen heeft voor zover bekend geen negatief effect op de motoren van vliegtuigen.

Door de toepassing van verschillende algensoorten en uiteenlopende kweek- en verwerkingssystemen is er een grote verscheidenheid aan mogelijkheden om tot algenkerosine te komen (Figuur B). Voorlopig is het niet mogelijk om een generieke 'optimale' algen-tot-kerosine route aan te wijzen. Dit komt enerzijds doordat de productietechnologie nog geoptimaliseerd moet worden maar anderzijds ook doordat de keuze van een productiesysteem sterk afhankelijk is van locatiespecifieke omstandigheden. Er valt zodoende ook geen eenduidige indicatie te geven van de opbrengst van algenbiomassa per hectare en de productieprijs van 1 liter biokerosine. In een theoretische casestudie hebben we op basis van Nederlandse omgevingscondities één scenario uitgewerkt (zie tekstkader).



Figuur B. Een vereenvoudigd schematisch overzicht van de verschillende mogelijkheden om algenkerosine te produceren

Algenkerosine productie voor de Nederlandse luchtvaart – een casestudie

In de case studie proberen we, op basis van aannames uit wetenschappelijke en grijze literatuur, tot een inschatting te komen van de mate waarin productie van algenkerosine in Nederland tegemoet zou kunnen komen aan de biobrandstofbehoefte van de Nederlandse luchtvaartsector. Met inzicht in de theoretische productie van algenkerosine in Nederland kunnen we een beeld verkrijgen van de belangrijkste kennisleemtes en ontwikkelpunten voor de algensector in Nederland.
In de casestudie is gerekend met een totaal jaarlijks gebruik van brandstof in de Nederlandse luchtvaartsector van 277 miljoen liter kerosine (gebaseerd op gegevens uit 2009). Daarnaast zijn er twee groeiprognoses van de brandstof behoefte in de luchtvaart tot 2020 berekend; bij een conservatief scenario van 1% jaarlijkse groei stijgt de vraag naar 309 miljoen liter in 2020 en bij een optimistischere prognose van 2% stijgt de vraag naar 344 miljoen liter. Sinds 1 juli 2011 is een mix van 50% biobrandstof en 50% traditionele kerosine toegestaan, wat inhoudt dat op basis van de gegevens in 2009 138,5 miljoen liter kerosine vervangen zou mogen worden door biobrandstof. In deze casestudie hebben we berekend in hoeverre aan deze vraag voldaan zou kunnen worden als 1% van de landbouwgrond besteed zou worden aan de productie van algenbiomassa.

Voor algenproductie zijn licht, nutriënten en water nodig. Verder is er ruimte nodig voor de kweekinstallatie. In Nederland is de lichtintensiteit vanwege de hoge breedtegraad relatief laag en de kosten voor grond hoog. Deze criteria hebben we meegenomen in een Multicriteria Analyse (MCA) om te bepalen welk productiesysteem in Nederland de hoogste potentie zou hebben. In de MCA hebben we ook energieverbruik, productiecapaciteit en productiekosten van de verschillende kweeksystemen meegenomen. Uit de MCA is gebleken dat de ”flat panel” fotobioreactor de grootste potentie heeft. Uitgaande van een oppervlakte van 1% van de beschikbare landbouwgrond, een opbrengst van 64 ton biomassa per hectare voor een flat panel fotobioreactor en een conversie factor van 0.21 om biomassa tot biodiesel om te zetten, zou in Nederland theoretisch 247 miljoen liter biodiesel geproduceerd kunnen worden.

Echter, bio*diesel* is niet geschikt voor de luchtvaart gezien de brandstof kan stollen bij lage temperaturen. Bio*kerosine* is wel geschikt voor de luchtvaart. Bio*kerosine* kan gemaakt worden uit algenbiomassa door middel van hydroprocessing. Van hydroprocessing van algenolie zijn echter geen goede conversiegetallen bekend, dus de gevonden waarde van 247 miljoen liter kan zowel een over- als een onderschatting zijn. De verwachting is echter dat hydroprocessing een minder efficiënte conversiemethode is. Als we er echter van uitgaan dat hydroprocessing even efficiënt is als de omzetting van algenolie naar biodiesel, dan kan 175% van de huidige brandstof behoefte in de luchtvaart voorzien worden en 140% van de behoefte in 2020 gestaafd aan de hoogste groeiprognose.

Met de theoretische potentie van algenkerosineproductie in Nederland kan volgens de berekeningen in principe aan de vraag naar biokerosine van de luchtvaart voldaan worden. Echter, de kosten van 1 liter algen bio*diesel* uit een lichtgedreven systeem wordt momenteel geschat op € 28,38 en productie van algen*kerosine* is naar verwachting nog duurder. Dit is een prijs die niet kan concurreren met traditionele brandstoffen. De verwachting is echter dat door toekomstige technologische ontwikkelingen en schaalvoordelen deze productieprijs drastisch omlaag zal kunnen. Qua locatie zal Nederland echter altijd suboptimaal blijven ten opzichte van zuidelijker gelegen locaties. Op locaties met een hogere lichtintensiteit is de opbrengst biomassa per hectare hoger. Op basis van de literatuur lijkt het verplaatsen van algenkweek naar een locatie met een hogere lichtintensiteit de productiekosten tot de helft te kunnen reduceren.

Discussie

Onderzoek aan de verschillende benodigde processen voor het produceren van algenbiobrandstof staat nog in zijn kinderschoenen. Er wordt veel onderzoek gedaan, maar aangezien de onderzoeken onder verschillende omstandigheden plaatsvinden en andere aannames aanhangen, lopen de resultaten sterk uiteen wat betreft de haalbare productie per hectare, de energiebehoefte voor de cultivatie, de verwerking van de algenbiomassa en productiekosten. Daarnaast wordt algenkerosine nog niet op grote, commerciële schaal geproduceerd (wereldwijd komt enkel het Amerikaanse bedrijf Solazyme het dichtst in de buurt van commerciële productie) en zijn de in beschouwing genomen studies allemaal nog in de pilot fase, waardoor de doorvertaling van deze data naar grootschalige productie grote onzekerheden met zich meebrengt. Hierdoor is het niet mogelijk om een precieze inschatting te maken van de potentiële productie in Nederland. De casestudie is gemaakt ter illustratie van de mogelijkheden en ter identificatie van de kennisleemten en van de belangrijkste ontwikkelpunten.

De huidige kweeksystemen van algen zijn hoofdzakelijk ontwikkeld voor de productie van hoogwaardige eindproducten voor bijvoorbeeld de farmaceutische industrie, de cosmetische industrie en de food/feed sector (relatief kleine afzetmarkten voor waardevolle algenproducten). Hierdoor is energiebesparing in het proces geen prioriteit geweest, waardoor de netto energie opbrengst van algenkerosine momenteel erg laag is. In de komende jaren zal moeten blijken of deze afzetmarkten verzadigd raken, waardoor afzetmarkten voor laagwaardiger eindproducten zoals biokerosine interessanter worden. Daarnaast moet gekeken worden in hoeverre er energie (en dus kosten) bespaard kan worden door optimalisatie van het productieproces van algenbrandstof.

Conclusie

Het is technisch mogelijk om biokerosine van algenbiomassa te maken. Het grootste voordeel van kerosine uit algenbiomassa is dat voor de productie van algen nauwelijks zoet water nodig is en de productie plaats kan vinden op locaties die niet geschikt zijn voor landbouw. Echter, op dit moment zijn de kosten van algenolieproductie dermate hoog dat het niet kan concurreren met de kosten voor traditionele brandstof. Daarnaast is de energiebehoefte van de productie van algenkerosine nog dermate hoog, dat momenteel slechts een kleine netto energiewinst wordt bewerkstelligd.

Om de productie van algenkerosine in de komende decennia rendabel te maken zullen gelijktijdige ontwikkelingen nodig zijn met betrekking tot de verschillende knelpunten in het productieproces van algenkerosine. Hierbij valt de grootste winst te behalen door 1) het selecteren/creëren van algensoorten met de optimale combinatie van kenmerken, 2) het optimaliseren van de pompsystemen benodigd voor kweek, waardoor er minder energie nodig is voor de toevoer van nutriënten en CO_2 en 3) het efficiënter maken van het verwerkingsproces dat nodig is om olie uit de algen te extraheren. Wat betreft locatie is grootschalige productie in Nederland niet rendabel gezien de lage lichtintensiteit; grootschalige productie zal op locaties buiten Nederland plaats moeten vinden. Om tot een economisch rendabel productieproces te komen zal, daarnaast, niet enkel op algenbrandstof gefocust moeten worden als eindproduct, maar zal een cascade van producten uit het productieproces moeten worden gerealiseerd. Verder is integratie met andere industrieën van groot belang om zo gebruik te kunnen maken van reststromen voor de aanvoer van de benodigde nutriënten en CO_2.

Op korte termijn is internationale multidisciplinaire samenwerking van overheden, onderzoekers en end-users/industrieën essentieel voor het verder ontwikkelen van een efficiënt geïntegreerd productieproces. Daarnaast is vooral geduld nodig om de aankomende periode van R&D te overbruggen die nodig zal zijn om tot een economisch rendabel product te komen.

De meningen verschillen over hoe lang het nog zal duren voordat algenkerosine op grote schaal geproduceerd kan worden. De optimisten stellen dat commercieel gebruik van algenkerosine al binnen 5 jaar haalbaar is, maar een meer algemeen gedeelde mening is dat het 10 tot 15 jaar zal duren.

Waardevolle exportproducten voor Nederland zullen de innovatieve ideeën en technologieën zijn, nodig voor algenkweek en niet de daadwerkelijke productie van algenbiomassa. De Nederlandse overheid zou de ontwikkeling van deze exportproducten kunnen stimuleren door langdurig vertrouwen in algenproducten uit te dragen. De focus zou hierbij moeten liggen op geïntegreerde, multidisciplinaire en *internationale* R&D programma's. Dit blijk van vertrouwen zal nodig zijn om de tijd te overbruggen die noodzakelijk lijkt om te komen tot technisch haalbare en commerciële toepassing van deze potentieel duurzame bron van biobrandstof.

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English Summary

In 2011, a Policy Paper on Aviation was accepted by the Dutch Parliament. The policy paper emphasizes the need for reduction of CO_2 emissions and the use of sustainable fuels to enable sustainable development of the aviation industry. Research and innovation will have to play a vital role in achieving this. The Dutch Ministry of Infrastructure and the Environment – Directorate-General for Civil Aviation and Maritime Affairs has requested Deltares to execute an exploratory study into the feasibility and potential benefits of using microalgae as an alternative energy source for the Dutch aviation sector.

This report aims to provide an overview of available knowledge and technologies in the field of algal kerosene production, to identify knowledge gaps and bottlenecks for large-scale commercial application, to give insight in the current feasibility of applying algal kerosene production to the Dutch aviation sector by presenting a case study and provide considerations on future economic feasibility of algal kerosene as a source of fuel.

Introduction
The biggest drawbacks of current sources for biofuel such as palm oil or jatropha are that significant amounts of fresh water and arable land are required for production. This leads to competition with food crops. Microalgae are recognized as a new source of oil. Oil-rich algae can be grown in saline water and do not require arable land, thereby overcoming the main drawbacks of other biofuels.

In response to the energy crisis in the 1970s, the U.S. Ministry of Defense started a research programme to investigate the feasibility of using algae as a source of fuel. As a result of the decrease in crude oil prices in the 1990s this program was ended. The peak in oil prices in 2008 boosted new interest in algal fuel. Research programmes were initiated worldwide to investigate the different processes required to produce algal fuel.

State of the Art
The four stages of the algal kerosene production process are:

- **algal strain selection**: which strain to use?
- **algae cultivation**: which cultivation system to use?
- **algae processing**: how to separate the algae from the growth medium (water) and how to extract the oil?
- **conversion to biofuel**: how to make kerosene out of algal oil (Figure A)?

Algal strain selection
There are many different algal species, all with different characteristics. Ideally, the algal species should have a high lipid content and high productivity; low nutrient requirements, a large tolerance to a wide range of temperatures and a robustness to stress in photobioreactors. A lot of research is being conducted in order to find the optimal algal species and algae are even genetically modified in order to enhance their productivity. However, at this time no known algal strain is capable of meeting all the stated requirements concurrently.

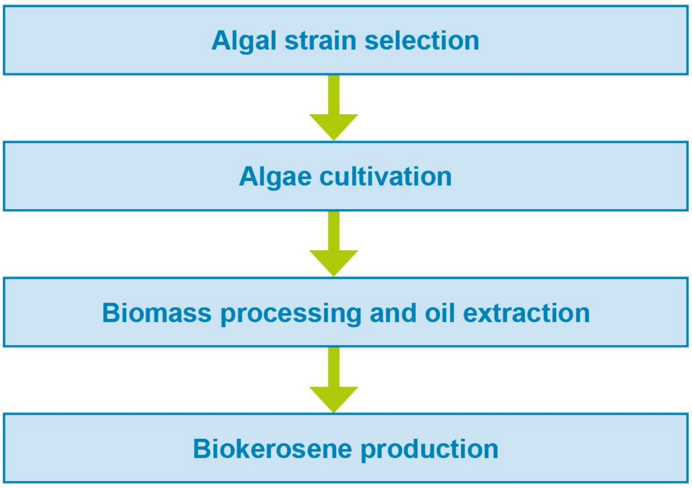

Figure A. A simplified schematic overview of the algal kerosene production process

Algae cultivation
There are several cultivation systems, of which we have taken into account the four most common in this report:

1 raceway ponds, algae are grown in shallow pools in open air
2 tubular photobioreactors (PBR's), a closed systems of tubes in which algae are cultivated
3 flat panel photobioreactors, cultivation in horizontally placed transparent vessels
4 heterotrophic production, algae cultivation in the dark with organic carbon as an energy source.

Each cultivation system has pros and cons. Raceway ponds are less costly, but have a high risk of contamination with other organisms than the desired cultivated species. Photobioreactors do not have this drawback, however nutrients and CO_2 need to be pumped through the culture, which requires a lot of energy and leads to stress within the algae, which could damage them. Heterotrophic cultivation has the highest yield per m^2, but needs organic carbon as energy source which is expensive as well.

Algae processing
After cultivation, the algae need to be separated from the culture. This is a difficult and energy consuming process. After this, the oil can be extracted from the algae.
At the moment, two methods exist to process algal biomass: a dry and a wet method. In the dry method, the medium containing the algal biomass is filtered, centrifuged and the remaining slurry is mechanically heat-dried, after which the cell walls are disrupted and the oil is extracted. In the wet method, the oil is extracted when the culture still has a relatively high water content. This method saves energy since limited or no mechanical drying is needed. However, this method is not yet feasible on a large-scale. After oil extraction, the oil has to be converted into kerosene through a process called hydroprocessing.

Algal kerosene application
As of July 1st 2011, ASTM International (an international standards organisation) officially approved the use of a mix of 50% petroleum kerosene and 50% algal kerosene in aircraft. Thus far, no adverse effects of biokerosene from algae has come to light.

Due to the large variety of different algal species and different cultivation and processing methods, there are many routes to producing algal kerosene (Figure B).
For now, it is not possible to identify one optimal algae-to-kerosene route. Therefore, it is also not possible to give an indication of the productivity per hectare or the price of algal kerosene per litre. In a theoretical case study we have used the Dutch abiotic conditions to develop one scenario for optimal production of algal kerosene (see text box).

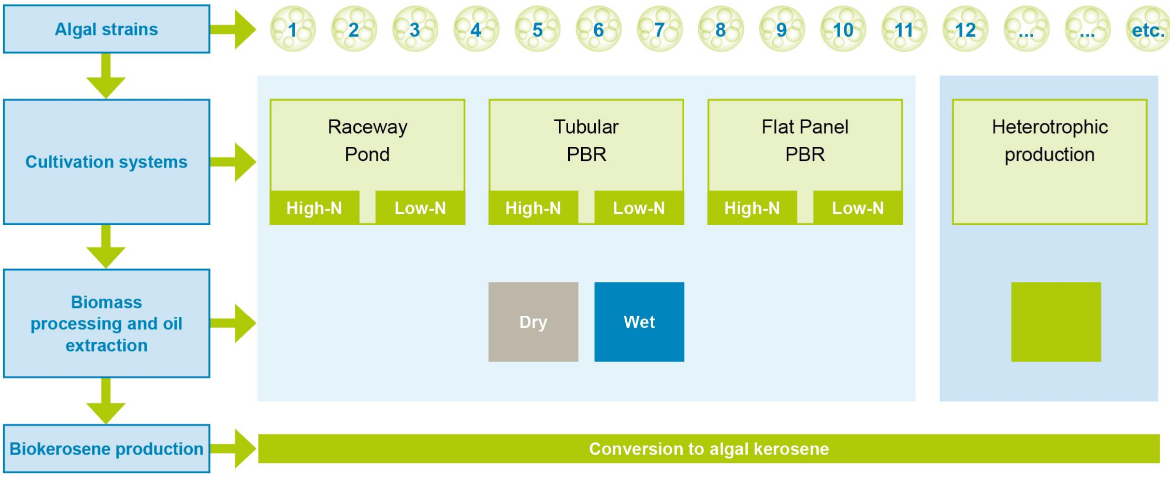

Figure B. A simplified schematic overview of the different ways to produce algal kerosene

Algal kerosene production for the Dutch aviation industry – a case study

In the case study, we aim to assess the extent to which algal kerosene production in the Netherlands could meet biofuel demands of the Dutch aviation sector, based on assumptions from scientific and 'grey' literature. With insight in the theoretical production capacity of algal kerosene in the Netherlands, we can gain understanding of the most important knowledge gaps and bottlenecks for the Dutch algal production sector.
In the case study, we used the total annual fuel consumption of the Dutch aviation sector, which is 277 million litres of kerosene (based on data from 2009). Also, we developed two growth scenarios of aviation fuel demand up until 2020; with a conservative scenario of 1% annual growth, the demand will increase to 309 million litres in 2010, with a more progressive scenario of 2% growth it will increase to 344 million litres. Since July 1st 2011, a mix of 50% biofuel and 50% traditional kerosene is allowed in the aviation industry, which would imply that based on 2009 data, 138.5 million litres of kerosene may potentially be replaced by biofuels. In this case study we calculated to what extent this demand could be met when 1% of arable land in the Netherlands would be devoted to algal fuel production.

Cultivation of algae requires light, nutrients and water. Furthermore, space is needed for the cultivation installation. Light intensity in the Netherlands is relatively low compared to the rest of the world and land costs are high. These criteria were included in a Multicriteria Analysis (MCA) to determine which cultivation system would have the highest potential for the Netherlands. Additionally, energy consumption, production capacity and production costs of the different cultivation systems were included in the MCA. The MCA results indicated that flat panel PBRs have the highest potential in the Netherlands. Based on the assumption that 1% of available arable land is used for algae cultivation, calculating with a maximum flat panel yield of 64 ton algal biomass per hectare, and a rough conversion factor of 0.21 to transfer dry biomass to biodiesel, theoretical production of algal biodiesel in the Netherlands could be up to 247 million litres.

However, bio*diesel* is not optimal for use in the aviation sector as components in the fuel could solidify at low temperatures. Bio*kerosene* can be used by the aviation sector and can be produced from algal biomass through a proces called hydroprocessing. Reliable conversion rates from algal oil to algal kerosene are not widely available, so the resulting amount of 247 million litres of biodiesel can be an over- or underestimation. It is however expected that hydroprocessing is a less efficient conversion method than conversion to biodiesel. When hydroprocessing is assumed to be as efficient then 175% of the current biofuel demand of the aviation sector can be met, and 140% of the biofuel demand in 2020, based on the highest growth scenario.

Theoretically, it would be possible to produce sufficient algal kerosene in the Netherlands to meet the biofuel demand of the Dutch aviation sector. However, the case study calculations provide an estimate of costs of 1 litre of algal *biodiesel* through cultivation in a PRB of €28.38. Production of algal *kerosene* is expected to be even more costly.
This price cannot compete with the price of traditional jet fuels. However, with R&D efforts and economies of scale, the algal kerosene production costs are expected to decrease significantly. As a location for cultivation, the Netherlands will remain a suboptimal choice.

On locations with a higher solar irradiation, the biomass yield per hectare can be significantly higher. Based on literature, we estimate that by relocating algae cultivation to a location with higher irradiation, production costs of algal kerosene could be up to halved.

Discussion

Research on the various processes in algal biofuel production is in its infancy. A lot of research has been done, but most research studies are done under specific circumstances and based on specific assumptions. This leads to a lot of variation in results on optimal yield per hectare, energy requirements for cultivation, processing of algal biomass and production and processing costs. In addition, algal kerosene is not yet being produced commercially on a large-scale (worldwide, only the US-based company Solazyme comes closest to commercial production) and the research studies evaluated in this study are predominantly in the pilot phase. Translating these (largely experimental) data to indications on large-scale production yields comes with large uncertainties. This makes it very difficult to make an accurate estimate of the potential production of algal kerosene in the Netherlands. The case study did however illustrate the possibilities and identify knowledge gaps and bottlenecks in the algae sector.

Current algae cultivation systems have been predominantly developed for the production of highly valuable substances for the pharmaceutical industry, the cosmetic industry and the food/feed sector (relatively small niche markets for economically valuable products of algae). Improving energy efficiency in these systems has therefore not been the biggest priority. A low net energy ratio is however crucial when producing biofuel. The following years will have to show whether these niche markets become saturated, so that markets for low value commodities become more interesting for producers of algae. This will strongly influence the development towards energy efficient (and thus cost-effective) production systems of algal kerosene.

Conclusion

It is technically feasible to produce biokerosene from algae. The largest benefit of kerosene from algae is that limited freshwater is required for production and production can take place in locations unsuitable for agriculture. However, at this moment algal kerosene production costs are too high to compete with traditional aviation fuels. Also, the energy requirements of algal kerosene production are still very high, which leads to a limited net energy return.

Several simultaneous developments on various bottlenecks in the algal kerosene production process are required in the next decennia in order to attain economic feasibility. Most developments are to be expected in 1) selecting and/or modifying algal species with optimal traits, 2) optimizing pumping systems, so less energy is needed to provide nutrients and CO_2 to the culture and 3) increasing efficiency of processing methods needed to extract the oil from the algae. Experts from the algae sector generally indicate that this R&D process could take about ten years.

Large-scale production in the Netherlands is not cost-effective due to low solar irradiation; in addition, by producing algae in the Netherlands, one of the benefits of algae production, i.e. that production does not have to take place on arable land, would be lost. Therefore, large-scale production should be implemented outside of the Netherlands. Also, production processes should not focus on algal fuels merely, but aim at realizing a cascade of products to reach economically feasible production. In addition, integration with other industries is essential for optimal use of nutrients, CO_2 and heat from waste streams.

In the following decade, international multi-disciplinary cooperation of governments, research institutes and end-users (industries) is essential for further development of efficient, integrated algal fuel production process. Patience is required to bridge the upcoming period of R&D that is required to attain economic feasibility of algal kerosene.

There are varying opinions on how long it will take before algal kerosene can be commercially produced on a large-scale. The most optimistic view is that commercial application of algal kerosene might be viable within 5 years, but a more commonly shared view is that it will take 10 -15 years before algae can be commercially used as an energy source.

Valuable Dutch export products will be innovative ideas and technologies in the field of cultivation and processing, rather than the actual production of algal biomass. A long-term push from the Dutch government is needed with a focus on integrated, multidisciplinary and *international* R&D programs. This is essential to bridge the time needed to optimize algal fuel production technologies required for commercial utilization of this potentially highly sustainable source of biofuel.

1 Introduction

1.1 Context of this report

In 2011, a Policy Paper on Aviation was accepted by the Dutch Parliament, concerning the government policy for the Dutch aviation sector. The policy paper emphasizes the need for reduction of CO_2 emissions and the use of sustainable fuels to enable sustainable development of the aviation industry. Research and innovation are indicated to play a vital role in achieving this

The Dutch Ministry of Infrastructure and the Environment – Directorate-General for Civil Aviation and Maritime Affairs has requested Deltares to execute an exploratory study about the feasibility and potential benefits of using algae as an alternative energy source for the Dutch aviation sector. This report aims to provide an overview of available knowledge and technologies in the field of algal kerosene production, identify knowledge gaps and bottlenecks for large-scale commercial application, give insight in the current feasibility of applying algal kerosene for the Dutch aviation sector, and provide considerations on future economic feasibility of algal kerosene.

1.2 Political context for alternative fuel

Volatile fuel prices

In recent years, interest in alternative fuel resources has increased due to large fluctuations in the crude oil prices. In the summer of 2008, the price of oil came close to $150 a barrel (Brent), representing up to 40% of airline costs. Then, as a result of the credit crunch, oil prices dropped to around $40 a barrel (Figure 1.1). Since January 2009 the prices have been rising steadily again to a current level of around $120 a barrel (www.iata.org).

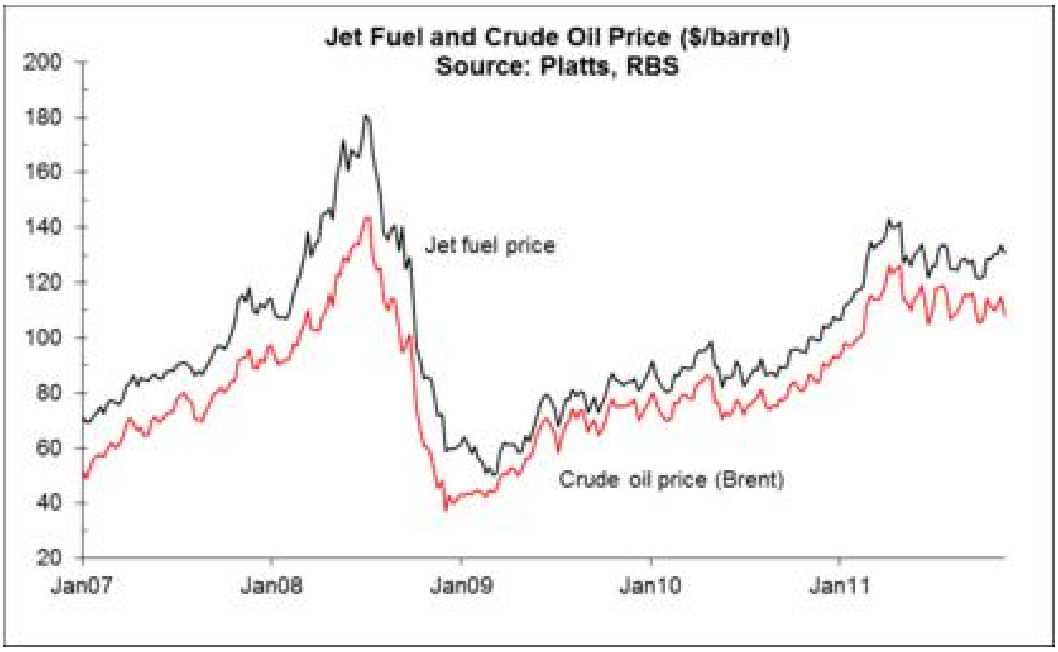

Figure 1.1 Variation in crude oil prices and jet fuel prices between January '07 and November '11 (Platss, RBS)

Expectations are that this volatility in oil prices will be ongoing due to a larger imbalance between demand and supply. Due to the development of emerging markets, the demand for energy resources will continue to increase. Main demand will come from China and the Middle-East. Secondly, it is unclear how much oil is left in the ground. There are no truly reliable figures available on the capacity of existing oil fields just as it is unknown how much countries are storing should a fuel crisis as in 1973 hit again. These factors have led to a high volatility in the fossil fuel prices, which has increased the urgency for development of alternative energy resources.

International climate agreements
The global aviation industry is responsible for 2% of global carbon dioxide (CO_2) emissions. By 2020, the Air Transport Association aims for at least an additional 25% improvement in fuel efficiency and CO_2 emissions, through technology and operational enhancements. Alternative fuels, particularly sustainable biofuels, have been identified as one of the key elements in helping achieve this goal (www.iata.org).

Carbon pricing methods
Various policy options are being considered by governments to address aviation's emissions. These include voluntary measures, fuel taxes and charges and emissions trading. The EU is a frontrunner in this: On 2 February 2009, European Union legislation came into force incorporating aviation into the EU Emissions Trading Scheme (ETS) starting in 2012. Virtually all airlines with operations to, from and within the EU fall under the scope of the directive, including non-EU airlines. Airlines covered by the EU ETS must meet certain requirements. In summary, these airlines are required to:

- Monitor tonne-kilometres and CO_2 emissions from 1 January 2010
- Report tonne-kilometre data by 31 March 2011
- Report CO_2 emissions data by 31 March 2011
- Apply for free emissions allowances by 31 March 2011
- Surrender allowances for 2012 emissions by 30 April 2013

Drawbacks of the implementation of the emissions trading system on a regional scale (EU) are effects of unequal competition and certain legal implications. Ideally, a global scheme should be implemented, but there is currently no global support for this.

Renewables
Due to the depleting world reserves of fossil fuel and the green house gas emissions associated with their use, it has become increasingly obvious that continued reliance on fossil fuel is not sustainable (European Commission 2007). Alternative, renewable, carbon neutral transport fuels are necessary for environmental and economic sustainability. An alternative fuel must be technically feasible, economically competitive, environmentally acceptable, and readily available (Brennan and Owende 2010). Possible alternatives to fossil fuel are the use of oils of plant or animal origin like vegetable oils and tree borne oil seeds to produce biodiesel fuel. This alternative diesel is called first generation biodiesel. This fuel is biodegradable and non-toxic and has low emission profiles as compared to petroleum diesel. Technology for producing first generation biodiesel has been known for more then 50 years and currently biodiesel is produced from plant and animal oils, for example: soybean oil, canola oil, animal fat, palm oil, corn oil, waste cooking oil and maize oil (Chisti 2007). First generation biodiesel has attained economic levels of production and it is projected that the growth of production and consumption of biofuels will continue in the coming decades (European Commission 2007). However, biofuels derived from terrestrial crops place an

enormous strain on world food markets, contribute to water shortage and precipitate in the loss of forests (Brennan and Owende 2010). Therefore, their potential for meeting the overall energy demands in the transport sector will most likely remain limited. Second-generation biofuels derived from lignocellulosic agriculture (plant biomass composed of cellulose, hemicellulose and lignin), such as Jatropha, address some of the aforementioned problems; however there is concern over competition for arable land.

Alternative fuels are seen as one of the key potentials to significantly reduce aircraft emissions in the future. Especially as prices of crude oil are expected to remain volatile, and as emissions price schemes are expected to be implemented at a large-scale. Kerosene based on microalgae is seen as one of the biofuels with highest potential benefits, as it has critical benefits over other renewable fuels (see below), can replace traditional kerosene with little or no modification of engines, and can be distributed through existing distribution systems (Mata *et al.* 2010).

1.3 Introducing algal biofuels

Microalgae have been suggested as very good candidates for fuel production because of their advantages in terms of higher photosynthetic efficiency, higher biomass production in less land area, and faster growth compared to other energy crops.

Crop	Oil yield (L/ha)	Land area needed (M ha)[a]	Percent of existing US cropping area[a]
Corn	172	1540	846
Soybean	446	594	326
Canola	1190	223	122
Jatropha	1892	140	77
Coconut	2689	99	54
Oil palm	5950	45	24
Microalgae[b]	136,900	2	1.1
Microalgae[c]	58,700	4.5	2.5

[a] For meeting 50% of all transport fuel needs of the United States.
[b] 70% oil (by wt) in biomass.
[c] 30% oil (by wt) in biomass.

Table 1: Comparison of different sources of biodiesel, yields, and land area needed for production (Chisti 2007)

Research in recent years has shown that third generation biofuel production using microalgae (from here on referred to as ‘algae’) has important advantages in comparison to other plant crops. Some species of algae can accumulate very high amounts of triglycerides, the major feedstock for biodiesel production (Chisti 2007). Additionally, algal biomass production is very high compared to first and second-generation biofuels (Table 1) and does not require high quality agricultural land for production and therefore does not compete with food production. Further more, algae can be grown in salt water. Therefore, algal production would not put extra pressure on earth’s already limited fresh water supply.

Algae are considered one of the most promising feedstocks for biofuel production, (Chisti 2007, Brennan and Owende 2010, Mata *et al.* 2010, Malcata 2011), although algae production is still in its infancy. Algae are not yet produced on a commercial scale sufficient to meet demand. However, worldwide research is being carried out on algal strains, production systems and harvesting methods, in order to develop the technology needed for economically viable scale up of production (Hu *et al.* 2008, Moellering and Benning 2009, Sialve *et al.* 2009, Wijffels and Barbosa 2010, Xu *et al.* 2011).

1.4 Reading instructions

The questions asked in this report concern **algal species selection** (which species is most suitable for production of algal kerosene?), **algae cultivation** (what is the optimal cultivation method; can cultivation be scaled up to meet the demand of the Dutch aviation sector; which and how much nutrients are required for upscaled algae cultivation? Is upscaling possible in the Netherlands?), **algae processing** (how much algal kerosene is produced from 1kg of dry algae, how much energy is needed for production of algal kerosene?), **algal kerosene content** (what is the energy content of algal kerosene; does it meet requirements of jet fuel?) and **overall economic feasibility for production in the Netherlands**.

Chapter 2 presents the state of the art regarding the different phases of algal kerosene production (selection, cultivation, processing), which addresses many of the above questions. Chapter 3 identifies knowledge gaps that have arisen in the state of the art and discusses several topics relevant for upscaling of algal kerosene production for commercial use. Chapter 4 discusses how the potential supply of algal kerosene in the Netherlands relates to the renewable fuel demands of the Dutch aviation industry. For this, the Dutch conditions relevant for algae production are identified, and a multicriteria analysis (MCA) is used to determine the optimal route for algal fuel production in the Netherlands, based on available knowledge and expert judgement. Chapter 5 discusses the main issues and bottlenecks of future algal kerosene application resulting from a case study, with input from Dutch algae R&D, production and end-user experts. Finally, general recommendations are given.

2 Algal kerosene: State of the Art

2.1 Overview of international playing field

2.1.1 Where did we start?

In response to the energy crisis in the 1970s, the U.S. Department of Energy's Office of Fuels Development initiated several programs to investigate the feasibility of alternative energy sources (Chisti 2007, Sialve *et al.* 2009). The driving force of these programs was to secure energy availability. Next to research on solar energy, research was started on the use of plant material as a source of transportation fuels. From 1978 to 1996, the U.S. Department of Energy's Office of Fuels Development funded a program to develop renewable transportation fuels from algae (NREL 1998). The focus of the program, know as the Aquatic Species Program (or ASP), was the production of biodiesel from high lipid-content algae grown in ponds, utilizing waste CO_2 from coal fired power plants.

This program mainly focused on two topics: finding algal species that produce a significant amount of oil, and investigating how algae grow under several conditions. Extremes of temperature, salinity and pH were tested as stress factors, as they were believed to enhance oil production of algae. Over 3000 strains of organisms were collected and screened during this program, in order to find the most productive strain.

In 1995 funding for this program was terminated as fossil fuel prices dropped in the '90s. Although the program was ended a solid basis was made for research on algae as a source for fuel (Sheeman *et al.* 1998).

From 1990 to 1999 Japan also financed a large research project called "Biological CO_2 fixation and Utilization" (Usui and Ikenouchi 1997). This ten year program not only focused on developing methods to reduce CO_2 emission by growing microalgae, but also on the development of high-density, large-volume culture systems for microalgae, which resulted in the first photobioreactors.

2.1.2 Where are we now?

The peak in oil prices in 2008 boosted new interest in biofuels (Figure 1.1). Thus far, to our knowledge, there is no industrial facility producing biodiesel from microalgae at industrial output levels. The studies undertaken on the subject have been restricted to lab and pilot studies. However, other biofuels have successfully been used in aviation.

The fist flight on biofuels by a commercial aircraft was executed in 2008 by Virgin Atlantic. A Boeing 747-400 flew from London to Amsterdam, carrying in one of its four fuel tanks a 20% mix of biofuel derived from coconut and babassu oil. In 2009 a *KLM Royal Dutch Airlines* jumbo jet circled above Holland for a couple of hours with 40 occupants, powered by a 50:50 blend of kerosene and camelina derived biofuel. This was the first flight fuelled partially by biofuel to carry passengers.
In 2010 a milestone was reached when the EADS, European Aeronautic Defence and Space Company, carried out a test flight. The airplane was fuelled with biofuel derived 100% from

algae. The algae oil was provided by Biocombustibles del Chubut. This is the first recorded flight were an aircraft flew on 100% algal oil.

On 1 July 2011 ASTM (American Society for Testing of Materials) has officially approved the use of algae- and other sustainably-derived biofuels in commercial and military aircraft. The revised standard (ASTM D7566-11: Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons) was approved and states that up to 50 percent bio-derived synthetic fuel can be blended with conventional commercial and military jet fuel (Jet A). This provides a critical step in the commercialization of advanced, low-carbon biofuels.

Companies that are now providing the biofuels used for aviation think “algae represent one of the most promising materials here because of their excellent potential oil yields. The key practical challenge lies in scaling up output to industrial volumes, and we hope that two new projects will result in new ways of overcoming this challenge” (Markku Patajoki, the Head of Neste Oil's Biotechnology Group).

2.1.3 Who are the main players internationally?

All over the world, initiatives have evolved towards producing biodiesel from algae. The interest in this eco-innovation has been growing significantly in the last five years. Universities, small businesses, airlines and oil companies are nowadays involved in the development of economically viable production of algal oil.

2.1.3.1 Airlines

Australian airline *Qantas* has signed a deal to research the use of the algae based aviation fuel developed by US company *Solazyme Inc.*

Lufthansa is now testing in a 6 month trial whether the use of alternative fuel produced by Neste Oil, will have an effect on the aircraft engines. It will compare an engine that has been fuelled with a 50/50 blend of biodiesel and traditional kerosene to the other engine on the aircraft which will be fuelled only with kerosene in order to test whether the blended biofuel has effects on the functioning of the engines. Results are expected by the end of 2011 (icao.org).

Recently, Continental Airlines flight 1403 was the first revenue passenger trip in the U.S. powered by a "green jet fuel" derived partially from genetically modified algae, provided by Solazyme Inc.. United Airlines announced in November 2011 that it had signed a letter of intent with Solazyme Inc., to buy 20 million gallons of algae-derived biofuel annually, to be delivered in 2014 (algaenews.blogspot.com).

2.1.3.2 Oil companies

Next to the aviation industry, large international oil companies are also interested in alternative energy sources.

Since 2007 Shell has been the majority shareholder in *Cellana*, a company set up to operate a pilot facility in Hawaii to grow marine algae and use it to produce vegetable oil for conversion into biodiesel. *Cellana* is a joint venture established by *Shell* and *HR BioPetroleum.* Shell plans to expand the 2.5 hectare pilot project to a 1,000 hectare facility in a first step, and afterwards to a full scale commercial 20,000 hectare plant. In early 2011, however, Shell announced a hold on further activities in the field of algae cultivation.

Conoco Phillips is involved in a $5 million, multi-year sponsored research agreement with the *Colorado Center for Biorefining and Biofuels*. Their aim is to convert algae into renewable fuel.

In 2009 *Exxon Mobil* launched a biofuels program. An alliance with the biotech company, *Synthetic Genomics Inc. (SGI)* was initiated to research and develop next generation biofuels from algae. Under the program, if research and development milestones are successfully met, *Exxon Mobil* expects to spend more than $600 million during the next five to six years. In July 2010 *Exxon* opened a greenhouse facility to grow and test algae and explained that if this venture meets research goals the company would spend more than originally budgeted in the next decade.

Universities
In the US, various universities have been working on algal jet fuels, including the universities of Virginia, San Diego and Arizona State. In Australia, Queensland University is one of the main players; in the UK, Cranfield University seems to be leading. Most universities work together with small R&D companies as well as with energy companies and airlines.

R&D companies
The most well known R&D companies are based in the US: Honeywell's UOP, Solazyme, Amyris, Sapphire Energy (San Diego, CA) and Heliae (Arizona). As an example, Heliae develops, designs, and delivers cost-effective technology solutions that enable sustainable, industrial-scale production of food, fuel, and bio-chemicals from algae. It has recently signed an MoU with Dutch company SkyNRG to work jointly on an algae-based jet fuel program (www.biofuelsdigest.com).

2.1.4 Who are the main players in the Netherlands?

2.1.4.1 Aviation sector

SkyNRG is a Dutch company with the mission of creating the market for sustainable, affordable jet fuel. The company is working with some of the world's leading airlines, integrating a complete supply chain for sustainable jet fuels into their short and long-term strategy.

2.1.4.2 R&D, production

In the Netherlands there are several companies focusing on algae production. The focus of the Dutch sector lies predominantly in research and development of algae production for various purposes (food, feed, cosmetics and biofuels). Large-scale commercial production has not yet been implemented. Some Dutch companies such as AF&F, AlgaeLink, Aquaphyto, Lgem, Ingrepro, Maris and Phycom have grown algae on a small scale for a number of years, focusing on niche markets such as food/feed or wastewater purification.

AlgaeLink is a manufacturer of commercial scale algae cultivation equipment and algae-to-fuel-technology. The company mainly produces photobioreactors, but also grows the algae themselves and develops extraction methods. The company has contracts with the US Air Force, who is now producing algae using AlgaeLInks' reactors. AlgaeLink also was involved in developing pilot projects with KLM (www.biodieselmagazine.com).

2.1.4.3 Research

At Wetsus, the Dutch centre of sustainable water technology, a research theme ‘biofuels from microalgae’ was started in 2008. The objective of this research program is to realize breakthroughs leading to the successful commercialization of a microalgae production process for biofuels feedstock. This research theme is supported by 13 companies and 7 PhD researchers focusing on different issues related to this process.

The latest development in the Netherlands is the five-year AlgaePARC project, which was launched on 17 June 2011. At the AlgaePark, three different outdoor photobioreactor designs will be compared in terms of photosynthetic efficiency, volumetric productivity, energy use, use of nutrients, water availability, robustness and scalability. In five years time they hope to have obtained sufficient basic information for the design of a large-scale production facility. This project is being coordinated by Wageningen University and Research Centre (WUR) and involves 18 corporate partners, both national and international.

2.2 Available technologies

In order to produce algal oil, different processes play a role. It starts with algal strain and site selection, then algae have to be grown. This can be done in several different cultivation systems. After cultivation, the algal culture has a 0.02-0.06% total suspended solids. The algae then have to be separated from the growing media, in order to extract the lipids from the cells. Subsequent extraction leads to lipids and free fatty acids, which can be turned into biodiesel in a well studied process called transesterification (Mata *et al.* 2010) (Figure 2.1). Algal oil can be converted into kerosene through hydroprocessing. As a lot less data is available on hydroprocessing of algal oil, this next section will also address transesterification. All of these stages in the production chain will be discussed in the following paragraph.

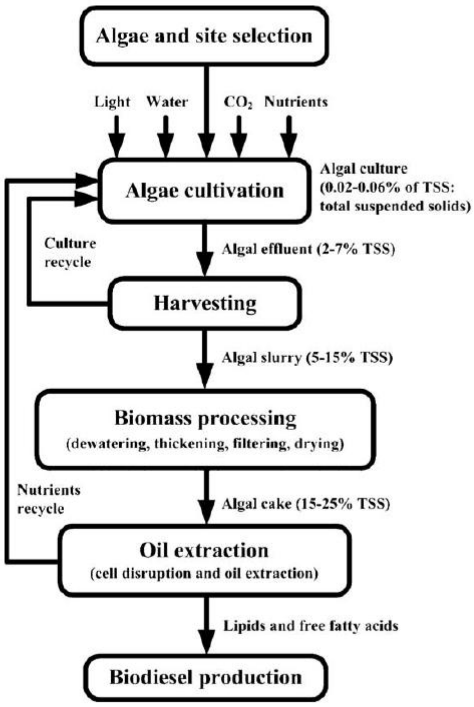

Figure 2.1 Chain stages of algal production (Mata et al. 2010)

2.2.1 Algal strain selection

The selection of appropriate algal strains is an important factor in the overall success of biofuel production from microalgae. Ideally, the algae should: 1) have a high lipid content and productivity; 2) have a high photosynthetic efficiency, and thus a high CO_2 sinking capacity; 3) have limited nutrient requirements; 4) be tolerant to a wide range of temperatures resulting from the diurnal cycle and seasonal productivity cycle. Depending on the production method the algal strain should also; 5) be robust and able to survive the stress common in photobioreactors or be able to dominate wild strains in open pond production. The above mentioned US Aquatic Species Program had collected over 3000 strains of oil-producing organisms, which, after screening, isolation and characterization, was narrowed down to 300 species, mostly green algae and diatoms (Sheeman *et al.* 1998). Currently, much effort is still being put into strain selection as all strains have different qualities (Table 2.1). Even though selection has been taking place, at the moment no known algal strain is capable of meeting all the stated biofuel production requirements concurrently (Brennan and Owende 2010).

Marine and freshwater microalgae species	Lipid content (% dry weight biomass)	Lipid productivity (mg/L/day)	Volumetric productivity of biomass (g/L/day)	Areal productivity of biomass (g/m²/day)
Ankistrodesmus sp.	24.0–31.0	–	–	11.5–17.4
Botryococcus braunii	25.0–75.0	–	0.02	3.0
Chaetoceros muelleri	33.6	21.8	0.07	–
Chaetoceros calcitrans	14.6–16.4/39.8	17.6	0.04	–
Chlorella emersonii	25.0–63.0	10.3–50.0	0.036–0.041	0.91–0.97
Chlorella protothecoides	14.6–57.8	1214	2.00–7.70	–
Chlorella sorokiniana	19.0–22.0	44.7	0.23–1.47	–
Chlorella vulgaris	5.0–58.0	11.2–40.0	0.02–0.20	0.57–0.95
Chlorella sp.	10.0–48.0	42.1	0.02–2.5	1.61–16.47/25
Chlorella pyrenoidosa	2.0	–	2.90–3.64	72.5/130
Chlorella	18.0–57.0	18.7	–	3.50–13.90
Chlorococcum sp.	19.3	53.7	0.28	–
Crypthecodinium cohnii	20.0–51.1	–	10	–
Dunaliella salina	6.0–25.0	116.0	0.22–0.34	1.6–3.5/20–38
Dunaliella primolecta	23.1	–	0.09	14
Dunaliella tertiolecta	16.7–71.0	–	0.12	–
Dunaliella sp.	17.5–67.0	33.5	–	–
Ellipsoidion sp.	27.4	47.3	0.17	–
Euglena gracilis	14.0–20.0	–	7.70	–
Haematococcus pluvialis	25.0	–	0.05–0.06	10.2–36.4
Isochrysis galbana	7.0–40.0	–	0.32–1.60	–
Isochrysis sp.	7.1–33	37.8	0.08–0.17	–
Monodus subterraneus	16.0	30.4	0.19	–
Monallanthus salina	20.0–22.0	–	0.08	12
Nannochloris sp.	20.0–56.0	60.9–76.5	0.17–0.51	–
Nannochloropsis oculata.	22.7–29.7	84.0–142.0	0.37–0.48	–
Nannochloropsis sp.	12.0–53.0	37.6–90.0	0.17–1.43	1.9–5.3
Neochloris oleoabundans	29.0–65.0	90.0–134.0	–	–
Nitzschia sp.	16.0–47.0			8.8–21.6
Oocystis pusilla	10.5	–	–	40.6–45.8
Pavlova salina	30.9	49.4	0.16	–
Pavlova lutheri	35.5	40.2	0.14	–
Phaeodactylum tricornutum	18.0–57.0	44.8	0.003–1.9	2.4–21
Porphyridium cruentum	9.0–18.8/60.7	34.8	0.36–1.50	25
Scenedesmus obliquus	11.0–55.0	–	0.004–0.74	–
Scenedesmus quadricauda	1.9–18.4	35.1	0.19	–
Scenedesmus sp.	19.6–21.1	40.8–53.9	0.03–0.26	2.43–13.52
Skeletonema sp.	13.3–31.8	27.3	0.09	–
Skeletonema costatum	13.5–51.3	17.4	0.08	–
Spirulina platensis	4.0–16.6	–	0.06–4.3	1.5–14.5/24–51
Spirulina maxima	4.0–9.0	–	0.21–0.25	25
Thalassiosira pseudonana	20.6	17.4	0.08	–
Tetraselmis suecica	8.5–23.0	27.0–36.4	0.12–0.32	19
Tetraselmis sp.	12.6–14.7	43.4	0.30	–

Table 2.1 Llipid content and productivity of different algal strains (Mata et al. 2010)

Additionally, some algae produce polyunsaturated fatty acids (Omega-3's). These high value products greatly enhance the overall marketability and economics of producing algae (Demirbas and Demirbas 2011) and might therefore also be taken into consideration in algal strain selection.

A genus that is commonly used is *Chlorella sp*., which appears to be a good option for biodiesel production because it is readily available and easily cultured in the laboratory (Miao and Wu 2006, Xu *et al.* 2006, Converti *et al.* 2009, Lardon *et al.* 2009, Fulke *et al.* 2010, Liu *et al.* 2011, Rasoul-Amini *et al.* 2011).

2.2.1.1 Genetic engineering

Genetic and metabolic engineering are likely to have an impact on the performance of algal strains and may provide important improvements in algal strains for biodiesel production. For instance improvements could be realized by increasing lipid accumulation in cells or by engineering pathways for novel biofuel molecules (Scott *et al.* 2010). Although the detailed molecular biology and regulation of lipid body metabolism is not fully understood in algae, two recent papers have made interesting observations. In both studies N-deprivation led to lipid accumulation up to 2.4 fold (Moellering and Benning 2009, Whang *et al.* 2009). For many algal species, lipid accumulation as a reaction to nitrogen deprivation comes at the cost of a lower growth rate (Converti *et al.* 2009). If the mechanisms of triglycerols and their accumulation in oil bodies were known, it could open the possibility of inducing lipid accumulation in oil bodies without having to apply stress factors (Wijffels and Barbosa 2010). For this, well annotated genomes need to be available.

Thus, genetic engineering offers the possibility for strain improvement (Wijffels and Barbosa 2010). However, there are still very few algae for which full or near full genome sequences have been obtained as has been done for *Chlamydomonas reinhardtii, Thalassiosira pseudonana* and *Phaeodactylum tricornutum.*

2.2.2 Algae cultivation

There are several different cultivation systems to produce algae. The three most commonly used cultivation systems for autotrophic micro organisms are 1) raceway ponds, 2) tubular reactors and 3) flat panel reactors, although all these cultivation types come in various configurations. Microalgae can also be grown without the use of light through 4) heterotrophic cultivation. The functioning, advantages and drawbacks of these four systems are discussed in this section.

2.2.2.1 Autotrophic cultivation

Raceway pond

Raceway ponds (Figure 2.2) are an open system with shallow, closed loop recirculation channels and a typical depth of 0.3 m. A paddlewheel provides mixing and circulation. The CO_2 requirement of the microalgae is usually satisfied from the surface air, but submerged aerators may be used to enhance CO_2 absorption. During daylight the culture is continuously fed in front of the paddlewheel where the flow begins. Broth is harvested

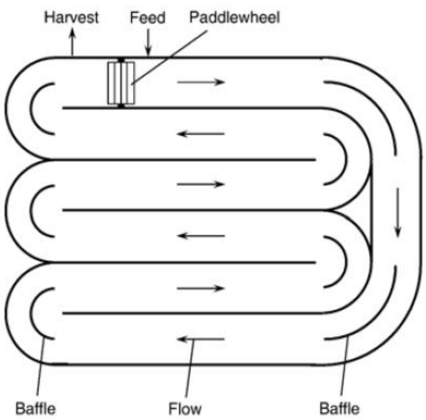

Figure 2.2 Aerial view of a raceway pond (Chisti 2007)

behind the paddlewheel on completion of the circulation loop (Chisti 2007, Brennan and Owende 2010).
The biggest advantage of raceway ponds is their simplicity, resulting in low production and operational costs. However, a major drawback is the fact that it is not possible to completely control the environment in and around the pond. Contamination of the pond with bacteria or other organisms can result in an undesired species taking over the desired species being cultivated. Other difficulties are the uneven light distribution throughout the pond, CO_2 deficiencies, inefficient mixing and water temperature fluctuations, all making the system less efficient (Brennan and Owende 2010, Mata *et al.* 2010).

To overcome the drawbacks of an open system, closed photobioreactors are used. Two types of photobioreactors that are commonly being used are tubular reactors and flatpanel reactors.

Tubular reactors

Tubular reactors (Figure 2.3) consist of an array of straight glass or plastic tubes. This tubular array is where the sunlight is captured. The algal culture is circulated by a centrifugal pump and a degasser is used to control the O_2 concentration. The main benefit of a photobioreactor is the possibility to grow a single species culture at high densities with lower risk of contamination. Due to the high densities of broth that can be attained, harvesting costs can also be reduced. However, tubular photobioreactors have design limitations on length of the tubes, as high O_2 concentrations reduce the algal productivity. Also CO_2 depletion and pH variation may affect production. Additionally the production and operational costs of tubular reactors are relatively high when compared to an open system (Chisti 2007).

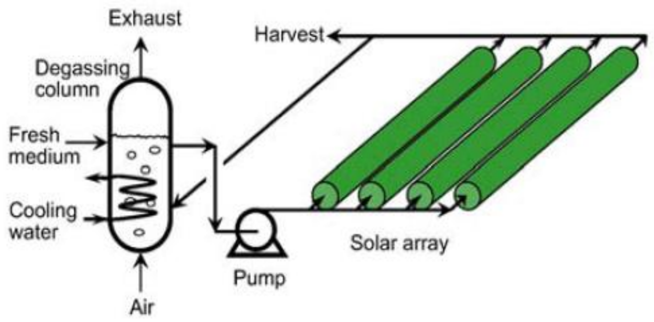

Figure 2.3 Tubular photobioreactor with tubes parallel run horizontal (ASD 2002, Chisti 2007)

Flat-panel reactors

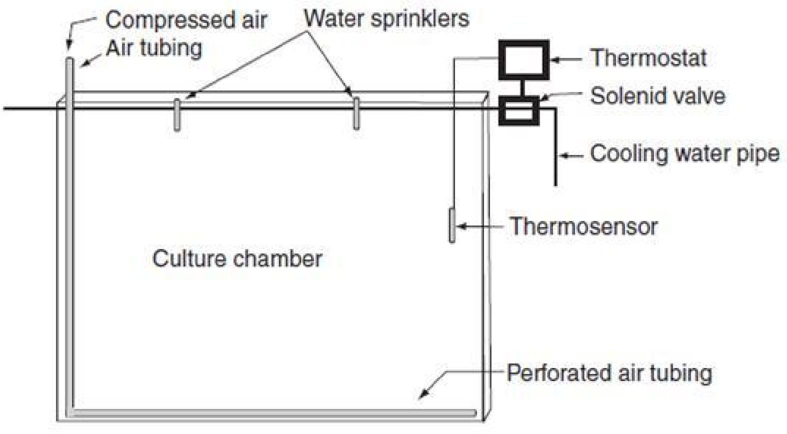

Figure 2.4 Flatpanel photobioreactor (Oilgae, www.oilgae.com)

A flat-panel photobioreactor (Figure 2.4) is a flat, transparent vessel in which mixing is carried out directly in the reactor with air sparging (injection of air or oxygen) (Cheng-Wu *et al.* 2001). Energy input for mixing is lower than for the equivalent tubular system. In addition flat panel reactors have lower O_2 accumulation (Scott *et al.* 2010).

2.2.2.2 Heterotrophic algae cultivation

Recent techniques have been developed for the large-scale cultivation of marine microalgae under heterotrophic growth conditions, by utilizing organic carbon such as glucose, acetate or molasses, instead of light as an energy source (Brennan and Owende 2010). Heterotrophic growth of microalgae is usually slower than autotrophic growth, generally about 2/3 of the growth rate of autotrophic growth with a typical growth rate of 0.3-1 d-1 (www.algae.wur.nl), however lipid content of the cells can be as high as 55% (Xiong *et al.* 2008). Heterotrophic algal cultures can attain up to 1,000 times higher densities than photoautotrophic cultures (FAO 1996) and since heterotrophic algal growth is independent of light energy, up scaling is much simpler than for autotrophic cultivation as smaller reactor surface-to-volume ratio's may be used (Li and Xu 2007). The resulting productivity per unit reactor volume is very high for heterotrophic cultivation. As it is a closed system, there is a high degree of control of and due to high cell densities harvesting costs are relatively low (Chen and Chen 2006). However, investment and operational costs are high as the organic carbon that serves as input for the algae has to be provided (algae.wur.nl).

2.2.2.3 Optimal cultivation system

Which cultivation system is economically most viable is heavily debated (Chisti 2007, Alabi *et al.* 2009, Brennan and Owende 2010, Mata *et al.* 2010, Scott *et al.* 2010, Demirbas 2011). This might be due to the fact that, to date, only pilot studies have been realized to produce algal oil thus far. Depending on initial conditions (climate, choice of algal strain, cultivation system) outcomes vary significantly. We have summarized the main characteristics of the different cultivation systems in Table 2.2.

Table 2.2 A comparative overview of four algae cultivation methods characteristics

Production system	Raceway pond	REF	Turbular reactor	REF	Flat panel reactor	REF	Heterotrophic fermentors	REF
Initial costs	Low, fairly simplistic system	(a)	High	(b)	High	(b)	High	(d)
Maintenance costs	low	(a)	high due to fouling	(c)	high due to fouling	(c)	unknown	
Operational costs	low	(b)	up to 10 times higher than open pond due to mixing	(b)	up to 10 times higher than open pond due to mixing	(b)	high due to organic carbon input	(e)
Energy input	low	(a)	high, due to mixing		high, due to mixing		high, due to mixing.	
Potential to scale up	Low due to large area needed	(a)	High potential	(c)	Low	(a)	Rather high	(d)
Photosynthetic efficiency	1,50%	(c)	3%	(c)	5%	(c)	n/a, grows in the dark	
Productivity (ton DW per ha)	21	(c)	41	(c)	64	(c)	70-120 g dw L-1	(e)
Risk of contamination	High, open system	(b)	Low, closed system	(b)	Low, closed system	(b)	Low, closed system	(d)
Oxygen build up	Low	(a)	very high	(a)	High	(a)	unknown	
temperature controle	difficult	(b)	more uniform	(b)	more uniform	(b)	more uniform	(e)
Hydrodynamic stress on algae	Very low	(b)	Very high due to turbulence	(b)	High due to mixing	(b)	high due to mixing	(d)
Land use	large space	(c)	0,5 of raceway pond	(c)	1/3 of raceway pond	(c)	unknown / less than raceway ponds	
Biomass concentration	low	(b)	3-5 times open pond	(b)	3-5 times open pond	(b)	up to 1000 times higher than open pond	(d)

(a) Brennan(2010)
(b) Mata (2010)
(c) Norsker (2011)
(d) Miao (2006)
(e) Algae.wur.nl (2011)

The most recent paper summarized in Table 3 was published by Norsker *et al.* (2011) who identified the dominant cost factors in algal oil production; these include irradiation conditions, mixing, photosynthetic efficiency of systems, and costs of medium- and carbon dioxide. Based on these cost factors, these authors compared three different cultivation systems operating on a commercial scale today, under Dutch climatic conditions. They found that algae under these conditions can be produced for a minimum of €4.15 per kg dry weight (Table 2.3). When optimal growing conditions on Bonaire are taken into account, in contrast to Dutch climate conditions, the study predicts that algae can be produced for € 0.70 ([$0.94 USD as of 30-11-11] Norsker *et al.* 2011).

Table 2.3 Unit biomass production costs (in cts, eurocents) from various capital and operational cost elements for raceway ponds, tubular photobioreactors and flat panel photobioreactors (Norsker et al. 2011)

(Base case)	Raceway ponds		Tubulars		Flat panels	
	cts kg^{-1} DW		cts kg^{-1} DW		cts kg^{-1} DW	
	1 ha	100 ha	1 ha	100 ha	1 ha	100 ha
Major equipment + power						
PVC liner	49.33	40.45				
Centrifuge	118.66	44.45	43.26	9.54	38.61	7.23
Power	17.02	19.12	3.65	3.96	2.54	2.99
Medium preparation	81.31	44.66	29.29	9.29	19.31	7.01
Power	3.80	4.20	0.84	0.81	0.64	0.61
Harvest buffer tank	25.11	18.84	6.28	3.89	4.09	2.94
Culture circulation pump			73.74	73.33		
Power			47.06	47.06		
Steel framework					11.73	11.73
Blower/paddle wheel	4.52	4.53	6.91	0.99	73.55	69.30
Power	3.17	3.18	5.83	5.79	240.67	240.67
Other capital						
Installation costs	41.84	22.94	47.84	29.11	44.19	29.46
Instrumentation costs	27.89	15.29	15.95	9.70	14.73	9.82
Piping	83.68	45.88	47.84	29.11	44.19	29.46
Buildings	83.68	45.88	47.84	29.11	44.19	29.46
Variable costs (ex. power)						
Polyethylene tubing/sheet			12.76	12.76	9.76	9.76
Culture medium	44.00	44.00	44.00	44.00	44.00	44.00
Carbon dioxide	33.67	33.67	33.67	33.67	33.67	33.67
Medium filters	44.42	44.42	18.39	18.39	13.88	13.88
Labour	579.55	12.56	289.78	6.28	188.58	4.09
Salary overhead	144.89	3.14	72.44	1.57	47.15	1.02
Maintenance	42.91	23.53	49.07	29.86	45.32	30.22
General plant overheads	342.35	19.85	93.39	17.09	128.65	18.87
Sum	1772	495	990	415	1049	596

2.2.3 Algae processing

To convert microalgae into liquid biofuels, algae have to be harvested, i.e. extracted from the growth medium and after that the lipids have to be extracted from the cells. This is a challenging phase in the production of algal oil. Low cell densities and small size of some algal species make the harvesting of biomass difficult. Currently there are two methods to extract lipids from microalgae; via the dry-route, oil extraction from dried microalgae and via the wet-route, oil extraction in the water phase.

2.2.3.1 Dry route

When lipids are extracted via the dry route, the algal slurry has to be pre-dried up to >85% dry weight before processing. To obtain this percentage of dry weight several techniques can be used. First algae are thickened by using chemical flocculation. After flocculation algae are either centrifuged to thicken the sludge further and then thermally dried, or only thermally dried (Figure 2.5) (Xu *et al.* 2011). The costs for the processes of drying algae up to the point where oil extraction can take place, are 85% of the total costs of algal oil production when algae are dried using only thermal drying (Lardon *et al.* 2009). Mechanical drying, such as filtration and centrifuging instead of thermal drying could hypothetically play an important role in reducing the total energy consumption, however these technologies have not been developed yet (Xu *et al.* 2011).

Lipid extraction

After the microalgae have been dried, lipid extraction can take place. Before biofuel production, triglycerols have to be extracted from the microalgal biomass. This is normally done by solvent extraction. Several solvents can be used such as hexane, ethanol, or a hexane-ethanol mixture. Although ethanol is a good solvent, it can also extract cellular components that can contaminate the desired product, i.e. the algal oil (Mata *et al.* 2010).
Other extraction methods such as ultrasound and microwave-assisted were also studied for oil extraction from vegetable sources. Converti *et al.* (2009) found that the most effective extraction method, from among those of classical extraction with the use of petroleum ether, the Folch method, and ultrasonic extraction, was the combination of ultrasonic extraction with the Folch method. The latter technique makes use of a mixture of chloroform and methanol combined with the use of ultrasound using petroleum ether as a solvent (Converti *et al.* 2009).

2.2.3.2 Wet route

In the wet route the algae are dried up to 30% dry weight. This is done first by flocculation, then centrifugation and mechanical drying (Figure 2.5). Cells are disrupted by a stirred bal mill and solvent extraction is used to extract the lipids (Xu *et al.* 2011).

A significant positive energy balance is achieved for both the dry and the wet route. The drying process in the dry route and the wet oil extraction in the wet extraction process consume a lot of energy. In the short term the dry route is more interesting because of a higher energy input/efficiency-output ratio, however, the wet route has more potential benefits in the long term as it produces biofuels with a higher value (Xu *et al.* 2011). The calculations done for both the dry and the wet route are based on extensive cultivation in open ponds. However, when producing in photobioreactors higher densities can be obtained, which may result in lower cost of dewatering (Xu *et al.* 2011).

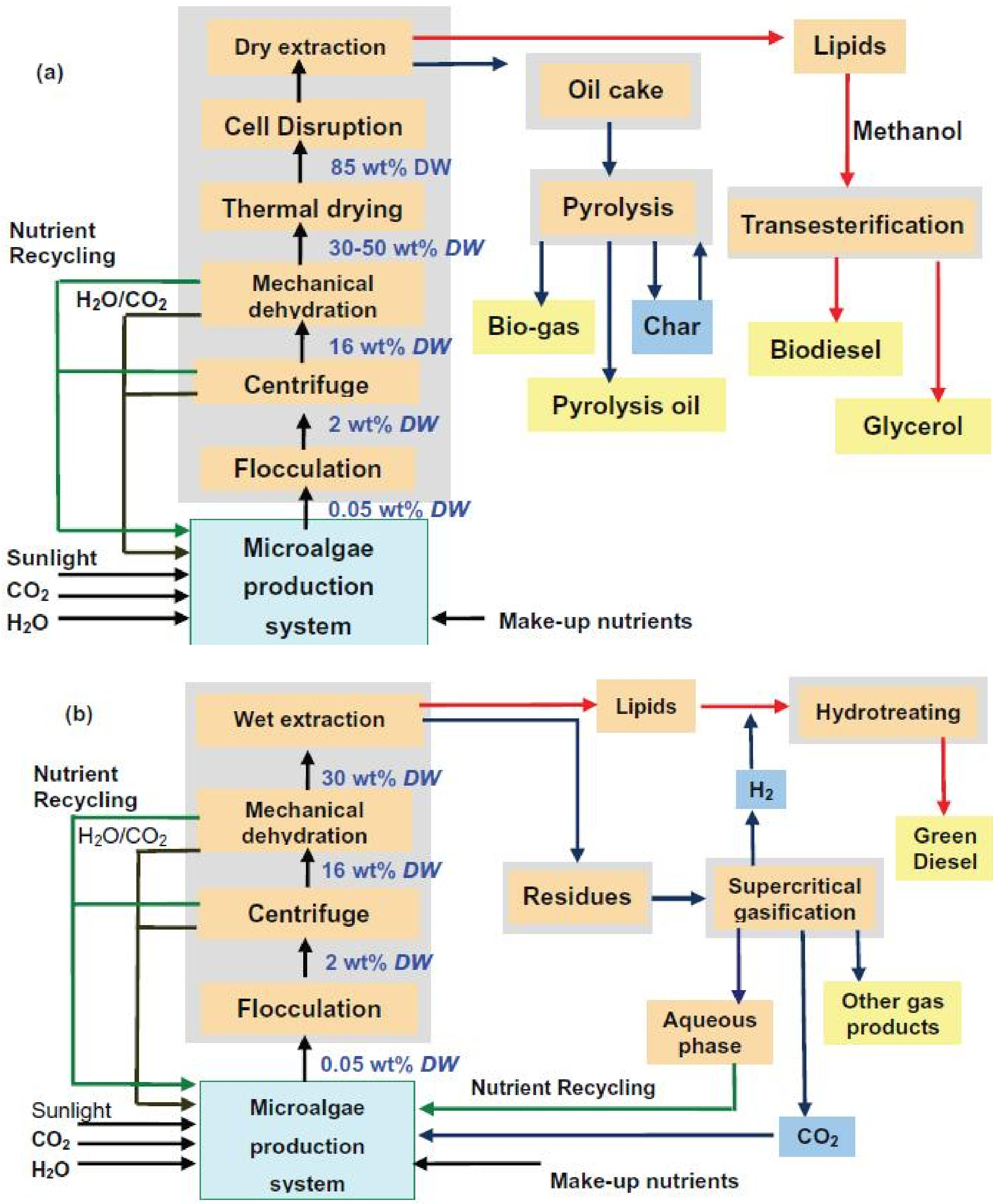

Figure 2.5 Schematic overview of the dry (a) and the wet (b) processing route (Xu et al. 2011)

2.2.3.3 *Conversion of algal oil into biodiesel*

After the extraction processes, the resulting algal oil can be converted into biodiesel. There are four primary ways to make biodiesel from oil: direct use and blending; micro-emulsions; thermal cracking (pyrolysis), and; transesterification (Ma and Hanna 1999). The most common way is transesterification as the biodiesel from transesterification can be used directly or ain blends with diesel fuel in diesel engines (Zhang *et al.* 2003). Transesterification is a chemical reaction between triglycerides and alcohol in the presence of a catalyst to produce the monoesters that are used as biofuels. Additionally in this process glycerol is produced.

2.2.3.4 Conversion of algal oil into kerosene: hydroprocessing

Biodiesel has about 80% the energy density of kerosene, but can solidify at the low temperatures of high altitude flight. However, with various hydroprocessing technologies used by petroleum refineries to catalytically remove impurities or reduce molecular weight, algal oils can be made into a kerosene-like fuel very similar to petroleum-derived commercial and military jet fuels (NREL 1998). The resulting fuel components, called hydroprocessed esters and fatty acids (HEFA), are identical to hydrocarbons found in jet fuel, but come from vegetable oil-containing feedstock (www.biofuelstp.eu). HEFA Synthetic Paraffinic Kerosene is produced by hydroprocessing plant, algal oils or animal fats. HEFA-SPK has also been called Hydroprocessed Renewable Jet or Hydrotreated Renewable Jet (HRJ) (www.airlines.org).

2.2.4 Algal kerosene application

To ensure that manufacturers do not have to redesign engines or aircraft and that airlines and airports do not have to develop new fuel delivery systems, algal kerosene must have the ability to directly substitute traditional jet fuel for aviation (known as Jet A and Jet A-1) and have the same qualities and characteristics. The industry is focused on producing biofuels from sustainable sources that will enable the fuel to be a “drop-in” replacement for traditional jet fuel. Drop-in fuels may be combined with the petroleum-based fuel either as a blend or as a stand-alone 100% replacement (ATAG 2009).

On 1 July 2011 the ASTM has officially approved the use of algae-based and other sustainably derived biofuels in commercial and military aircraft. The revised standard (ASTM D7566-11: Specification for Aviation Turbine Fuel Containing Synthesized Hydrocarbons) states that up to 50 percent bio-derived synthetic fuel can be blended with conventional commercial and military jet fuel.

Lufthansa is now testing in a 6 month trial whether the use of alternative fuel will have an effect on the aircraft engines. It will compare an engine that has been fuelled with a 50/50 blend of biodiesel and traditional kerosene to the other engine on the aircraft which will be fuelled only with kerosene. Results are expected by the end of 2011. Tests done by Boeing showed that there are no adverse effects on any of the aircraft’s systems (Kinder and Rahmes 2009). As this report focuses on the feasibility of algal diesel with respect to oil and CO_2 emission prices, the effects of the use of biodiesel in aircraft will not be further discussed in this report.

2.3 Algal oil properties

From 1 kg dry algae, 0,22 litre of algal oil from can be produced. 22 litres of algal oil are needed to produce 21 litres of biofuel (Person 2010). Thus far the effect of using algal oil on engine emissions have not been studied. For other biofuels these studies have been done, with different results for $N0_x$ emissions, depending on engine load conditions, engine type, operation temperature etc. The use of biodiesel leads to the substantial reduction in PM, HC and CO emissions (Xue *et al.* 2011). Most studies show that there is a slight $N0_x$ increase when first generation biodiesels are used (Lapuerta *et al.* 2008), with the most commonly used equation showing a 10% increase when 100% biodiesel is used (Figure 2.6) according to the Assessment and Standards Division by the US Environment Protection Agency (ASD 2002). As microalgae have a higher nitrogen content than first generation biodiesel (Table 2.4), the $N0_x$ emissions when algal oil is used may prove to be higher.

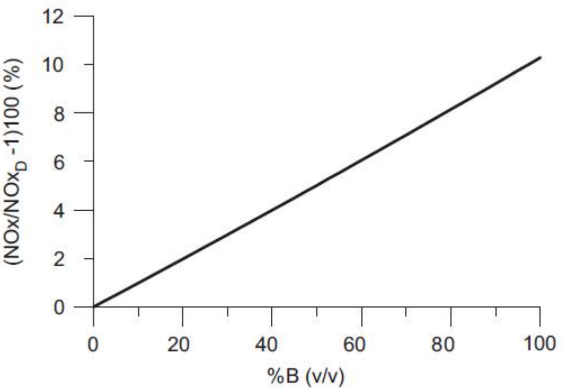

Figure 2.6 Mean increase in NOx emissions as the biodiesel content increases (for heavy-duty engines with no EGR or after treatment system) (ASD 2002)

This chapter has provided an overview of the available technologies in the field of algae production and processing. However, it has also shown that there are knowledge gaps that pose a bottleneck for large-scale production of algal kerosene. Optimal algal strains have not been identified, cultivation and processing methods are still very energy consuming and under constant development, and upscaling experience is very limited at present. These knowledge gaps and uncertainties make it difficult to predict the potential benefits of the algae cultivation sector to respond to algal kerosene demand. The following chapter identifies and discusses these knowledge gaps further and discusses the optimal potential of algae as a source of aviation fuel for the Dutch aviation sector.

Table 2.4 Comparison of typical properties of fossil oil and bio-oils from wood and microalgae.

Properties	Typical value		
	Bio-oils		Fossil oil
	Wood	Microalgae	
C	56.4%	61.52%	83.0–87.0%
H	6.2%	8.50%	10.0–14.0%
O	37.3%	20.19%	0.05–14.0%
N	0.1%	9.79%	0.01–0.7%
S	–	–	0.05–5.0%
Density	1.2 kg/l	1.16 kg/l	0.75–1.0 kg/l
Viscosity (Pa s)	0.04-0.02 (at 40 °C)	0.10 (at 40 °C)	2–1000 (depends on factors such as temperature, density and its contents)
Heating value	21 MJ kg^{-1}	29 MJ kg^{-1}	42 MJ kg^{-1}
Stability	Not as stable as fossil fuels	Not as stable as fossil fuels, but more stable than the bio-oil from wood	

3 Algae as a source of aviation fuel: knowledge gaps and bottlenecks

3.1 'Many ways to Rome'

The figure below provides a simplified overview of how we see the various options in the development of algal kerosene. With various algal species and strains used for cultivation (with varying characteristics), several cultivation systems (each with pro's and con's) and multiple processing methods (at different stages of development), the number of possible algae-to-kerosene routes is large (Figure 3.1).

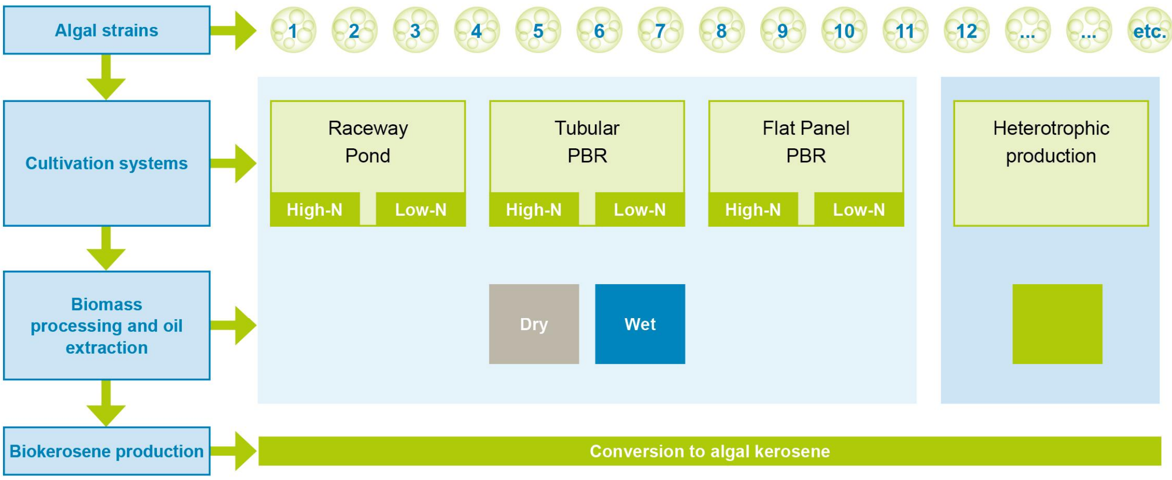

Figure 3.1 A simplified schematic overview of the various options in the algal kerosene production process (PBR: photobioreactor)

3.2 Algal species selection

Many different algal species are currently being used in algae cultivation, all with their own characteristics, of which the genus *Chlorella* is most used. R&D in this field is strongly developing, as is the field of genetic modification. A lot of knowledge has been developed on the characteristics of different algal species, their growth requirements and their optimal growth potential; results show that maximum yield and oil content can differ largely between species. The selection of species to be used for algal kerosene production depends on various factors: cultivation method used, solar radiation (not all species can tolerate all levels of radiation), and availability of nutrients. Some species may have a high yield in raceway ponds, but might not do well in PBRs. It is therefore not yet possible (nor desirable) to identify 'the optimal' algal species for algal kerosene production overall.
The optimal algal strain is dependent on the location-specific conditions and preferred end- and by-products. The selected algal strain determines the optimal cultivation system.

3.3 Algae cultivation

Four main algae cultivation methods have been described: two types of photobioreactors (PBRs), the raceway pond method and the heterotrophic method. All of these methods are strongly under development; optimization of culture systems is ongoing. The different cultivation systems each have their beneficial aspects (raceway ponds are generally cheaper than PBRs), but also their drawbacks (raceway ponds are more sensitive to contamination and require a larger land area). The weight of their benefits and drawbacks is strongly location dependent, as land cost and availability, nutrient availability, solar radiation and level of technology infrastructure may lead to a preference for one type of system.

Heterotrophic cultivation
Regarding heterotrophic cultivation, the grey literature generally states that production is independent of light, however this is not exactly the case. Required organic material as input for the heterotrophic system (glucose, glycerine) comes from primary production, which in itself requires light and other nutrients. When calculating the required energy input for heterotrophic cultivation, the energy needed for that primary production needs to be taken into account as well. Most literature studies included on the state of the art neglect to include this factor. When included, heterotrophic cultivation will probably require most energy input of all cultivation systems, but lack of data is this field at present makes it difficult to draw a conclusion.

Weighing selection criteria
Based on the occurrence of contamination (lower yield per ha, unstable quality of product) and higher land-use (higher costs, competing with food crops), one could prefer PBRs over raceway ponds. However, there are several important criteria on which an optimal cultivation system can be selected, such as productivity, energy requirements, possible by-products, operational and maintenance costs.
It is essential to determine which criteria are most important in the selection of an optimal cultivation system. The weight of these criteria however depends strongly on the local situation (i.e. solar irradiation, availability of land, water and nutrients).

The state of the art has shown a large variation in energy requirements of the different algae cultivation methods, but an even larger variety of results of different studies. This variation in results makes it difficult to include ‘energy consumption’ as a reliable criterion to select the ‘optimal’ method for algal kerosene production.

3.4 Processing

Much work is being done in the field of processing of algal biomass. Processing appears to be one of the most important factors determining the total energy budget together with the total costs of algal kerosene production. The dry processing method is now the method most widely used, while wet processing is in its infancy and currently very expensive. However, it is likely that the (expected) benefits of wet processing (enhanced nutrient recycling, reduced drying efforts) will lead to an increased focus on R&D on this wet method. It is difficult to predict how fast these developments will occur, what the ultimate potential of wet processing will be, and how much processing costs could ultimately be reduced.

Development of effective wet processing technologies could lead to large changes in the algal kerosene production process in terms of input and costs. Rough predictions of processing costs through the wet route are accompanied by strong assumptions and large uncertainties.

Nutrient recycling
The biomass of algae generally consist of 7% nitrogen and 1 % phosphorus, therefore, for the potential Dutch supply of 1,184,000 tons dry weight (DW) per year, at least 83,000 tons of nitrogen and 12,000 tons of phosphorus are needed. This is almost 10% of all fertilisers annually produced in all of Europe (Egmond *et al.* 2002).
With upscaling of algae cultivation to meet the expected demand for algal kerosene for the Dutch aviation sector, it is likely that nutrient availability will become a critical (cost) factor in the Netherlands. Nutrient recycling is bound to become essential for cost-effective and sustainable upscaling. As nutrient recycling is currently not yet feasible in available processing methods, this will most likely become a main R&D topic in the field of processing, ultimately working towards stand-alone systems: the ultimate aim is to design a cultivation system that is independent of the supply of nutrients. Such stand-alone systems could, in principle, be possible as algae contain nitrogen and phosphate, but the oil harvested from algae does not.

3.5 Algal kerosene content

Properties of algal kerosene and normal kerosene differ slightly, but aviation infrastructure (e.g. engines) does not need to be adjusted for the use of algal kerosene. Currently, mixing of kerosene and biokerosene in a 50/50 mix is allowed and feasible. Our preliminary assessments indicate that the algal kerosene supply is expected for some time to be limiting for the application of algal kerosene in the aviation sector, making it uncertain whether it is feasible to exceed a 50/50 algae/petroleum-kerosene mix in the following decades.

3.6 Economic feasibility

It is very complex to determine the economic feasibility for application of algal fuel in the aviation industry due to a number of issues.

Currently, the production costs per litre of algal oil are very high, mainly due to small-scale production. It is expected that production costs will decrease significantly due to upscaling, but data on this varies significantly in the literature.

Also, the state of the art has shown that there is such a huge variety in available algal species, cultivation systems and processing methods, which makes it very difficult to determine the most optimal ‘algae-to-kerosene production route’ that could potentially be competitive with fossil fuels in the long-run.

Another complexity is that the ‘most promising route’ differs per location. Which algal strain or cultivation method combination has the best potential highly depends on location-specific characteristics such as availability of nutrients, availability (cost) of land, and solar radiation.

Furthermore, what would be identified as the most optimal algae-to-kerosene route now is not necessarily the most optimal route in the future. Technological developments in the sector are ongoing, and the speed and extend of these are unclear. Expectations are that production costs will decrease significantly due to upscaling and technological improvements, but this will also highly depend on the extend of R&D efforts, and relative availability and costs of fossil fuels, which are in turn related to (inter)national renewable energy policies and the application of ‘competing’ renewables.

Taking the above complexities into account it becomes clear that it is necessary to focus on a specific area or case study to determine the possible economic feasibility of algal kerosene. For this reason, chapter four will discuss the hypothetical case of the Netherlands. The optimal ‘algae–to-kerosene production route’ for the Netherlands will be identified based on a multicriteria analysis. For this optimal route the current production costs of algal kerosene will be calculated. Also the potential amount of algal kerosene that can be produced in the Netherlands will be determined based on availability of land, taking into account the limiting factor of nutrient availability. This will provide us with an indication of the extent to which production in the Netherlands could be able to meet the expected demand of the Dutch aviation sector until 2020.

3.7 Environmental aspects of algal kerosene production

Water use
Microalgae can be grown in either fresh or saline water. The most significant water loss will occur in open ponds where evaporation is prevalent. Water demand estimates suggest that the projected consumptive water loss from evaporation could fall into the range of 240 to 600 litres of water for each litre of algal oil produced (Pate *et al.* 2011). This does not include downstream post harvesting into products. Downstream processes have an estimated water use of 2-10 litres per litre of fuel produced (Pate *et al.* 2011).
The high water use in raceway pond production systems can make this production type unsustainable when scaled up for commercial production. Tubular and flat panel photobioreactors will most likely experience less evaporation. However, to make algae production sustainable, approaches that allow for the use of marine and other non-fresh surface water such as waste water, brackish or saline ground water are needed (Cooney *et al.* 2011).

Waste products
For production of bio kerosene, only the algal oil is needed and lipid free biomass containing proteins is the by-product. As already mentioned, at this time recycling of nutrients is not possible when algae have to be dried up to 80% dry weight before processing. This means that all nutrients used in the process will end up as waste. However, new methods are now being developed to replace this unsustainable processing method (Xu *et al.* 2011).
Since algal kerosene cannot be produced at a commercial scale yet and the process of producing algal kerosene is still undergoing major developments, it is hard to define the by-products of commercially produced algal kerosene. This will be highly dependent on the cultivation and processing methods used.

Greenhouse gasses
Relative to fossil fuels, sustainable produced algal kerosene results in a reduction in CO_2 emissions across their lifecycle. Carbon dioxide absorbed by algae during the growth of the biomass is roughly equivalent to the amount of carbon produced when the fuel is burned in a combustion engine – thereby returning the CO_2 to the atmosphere. This means that algal kerosene could be approximately carbon neutral over its life cycle. However, emissions are produced during the production of algal kerosene, from the equipment needed to grow the

crop, transporting the raw goods, refining the fuel and so on. Furthermore, energy needed for cultivation and processing is now derived from fossil fuels. The exact reduction in overall CO_2 lifecycle emissions is not yet known for algal kerosene. However, for second generation biofuels a reduction of 80% in overall CO_2 lifecycle emissions is estimated compared to fossil fuels (ATAG, 2009). Given the high energy demands when producing algal biofuel (e.g. mixing and processing) this reduction in emissions will be lower for algal kerosene, but might still prove to be significant compared to fossil fuels.

Autotrophic algae growth and biomass production is enhanced with the input of supplemental CO_2. This can potentially be supplied from stationary industrial sources such as cement plants, fermentation industries (ethanol plants, cheese factories, etc.), and flue gas from fossil-fired power plants (Kadam 1997).

To make algal kerosene a truly sustainable fuel, energy input needed for production should be from alternative energy sources. Additionally, CO_2 input for production should come from fermentation industries (ethanol plants, cheese factories, etc.) instead of fossil-fired power plant to make sure no additional net CO_2 is released into the air when burning the algal kerosene.

4 A case study for large-scale production of algal kerosene in the Netherlands

Chapter 4 first identifies the Dutch conditions relevant for production of algae. A multicriteria analysis (MCA) is used to determine the optimal route for algal fuel production in the Netherlands based on available knowledge and expert judgement. Subsequently this route is used to calculate the potential algal kerosene production in the Netherlands. We then discuss how this potential supply relates to the renewable fuel demands of the Dutch aviation industry.

The following case study presents a hypothetical case of algal kerosene production in the Netherlands. We make assumptions on upscaled productivity, production costs, availability of land and land costs, based on the state of the art as well as on expert judgement. We are aware that large variations in results and data from the state of the art will inevitably lead to large uncertainties in the outcomes, but we aim to use this case merely to gain insight into the order of magnitude of production capacity and production costs, and to identify bottlenecks specific to the Dutch situation.

4.1 Relevant conditions for algae production in the Netherlands.

Algae need water, light and nutrients to grow. If algae cultivation is implemented in a controlled environment such as a raceway pond or a photobioreactor, suitable space is also required for the plant to be built on. Of the main criteria that influence production, irradiation levels and land costs show the largest variation across the globe (Figure 4.1). This chapter will focus mainly on irradiation levels and land costs.

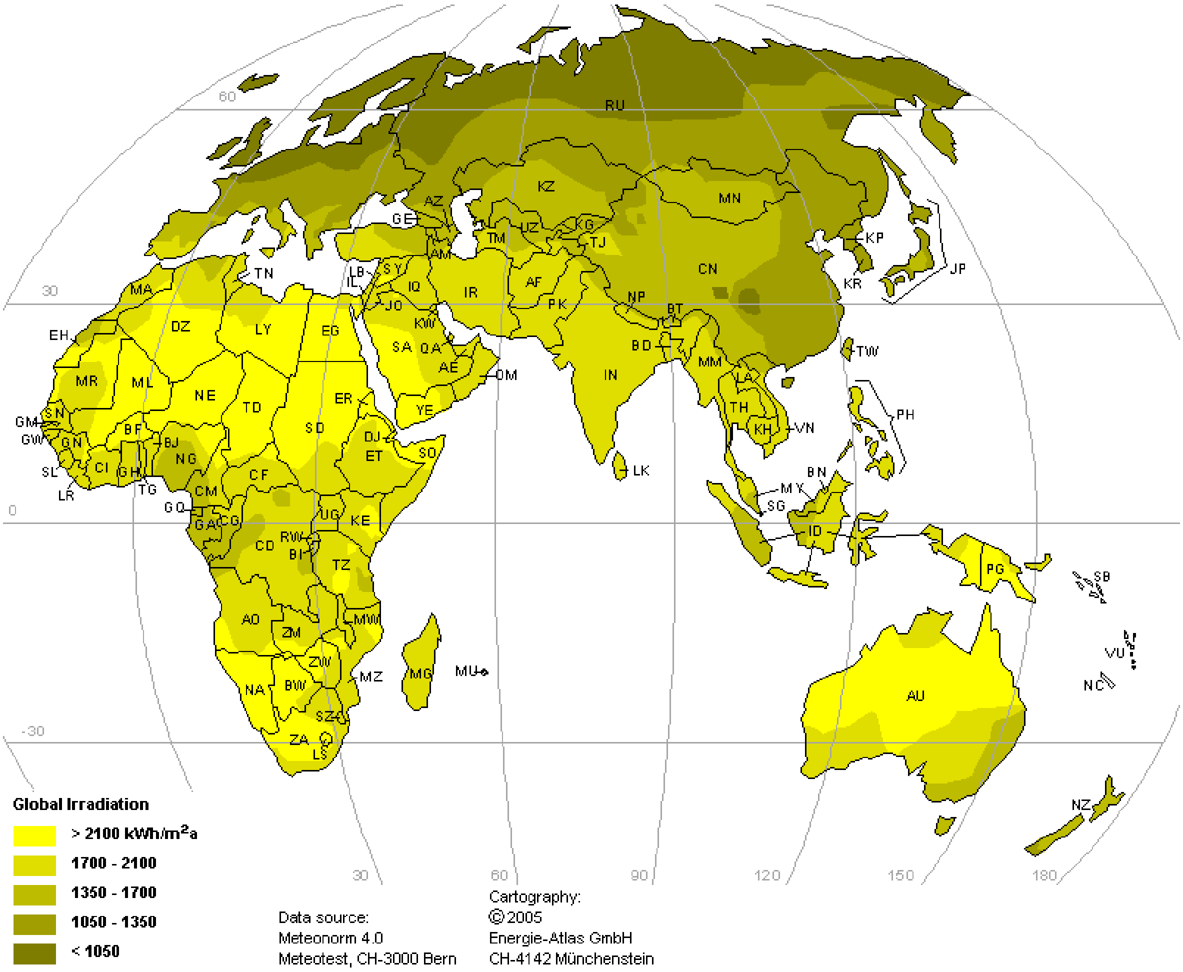

Figure 4.1 Global yearly solar irradiation

The Netherlands has a solar irradiation level of less than1050 kWh/m^2 per year when cloud cover is taken into account (Figure 4.1). This is less than half of the highest solar irradiation level which is found in the major deserts of our planet.

Land cost

The Netherlands has one of the highest population densities in the World with 401.4 inhabitants per km^2 (2011), which makes the Netherlands among the top 30 most densely populated countries in the world (Figure 4.2). This makes the demand for land in the Netherlands high, which results in high land values. Of the total surface area of the Netherlands, around 66% is used for agriculture. Roughly, 14% consists of forest and nature. The remaining 20% of the land area is comprised of urban and industrial areas.

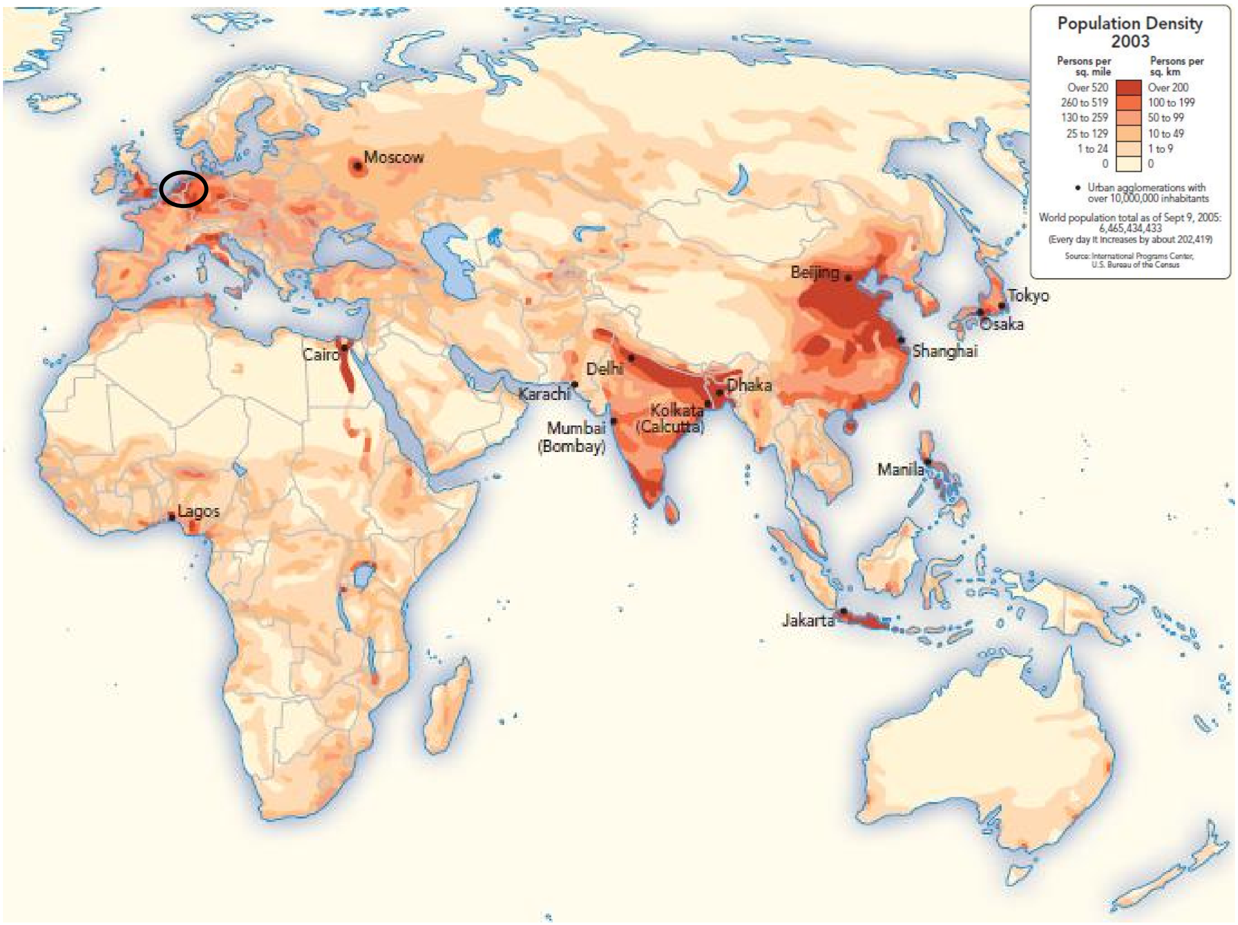

Figure 4.2 Global overview of population density in 2003 (Source: International Programs centre, US bureau of the census)

Compared to other large countries in the European Union, the price of farm land in the Netherlands is exceptionally high, mainly caused by the scarcity of (farm) land. In February of 2009, the average price for unrented surface per hectare was € 45.000 per hectare (according to Dutch real estate association NVM Agrarisch Onroerend Goed, www.nvm.nl). In comparison: the price of one hectare of farmland in Germany was on average around €9.000 in 2006 (€29.000 in 2006 in the Netherlands). Prices paid per region however vary considerably, and in some regions similar farm prices as in the Netherlands are paid. Also in the Netherlands, prices differ considerably by region and with type of soil (and whether or not the land has a rental contract). In the new member states prices for one hectare of land are lowest in the EU, around €1.500-2.000 per hectare.

4.2 Optimal algae-to-kerosene route for the Netherlands

To determine the optimal algae-to-kerosene route for the Netherlands, it is necessary to identify the optimal algal strain and cultivation method. Based solely on light sensitivity of algal species, it could be possible to make a selection of optimal algal strains for cultivation under solar irradiation levels in the Netherlands. Light sensitivity is however only one of many criteria to consider when selecting for an optimal strain, and extensive work is now being done on strain selection optimisation. We have therefore opted to focus on selecting an optimal cultivation method, and make use of the optimal algal strains used by Norsker *et al.* (2011). By using this information we will not obtain the highest potential production (by selecting the strain with maximum productivity), but a realistic proxy for the most feasible production.

In the overview of the state of the art we have summarized the pro's and con's of four different cultivation systems (Table 2.2). To identify the most optimal cultivation system for the Netherlands, a multicriteria analysis was conducted. A multicriteria analysis was chosen to be able to compare the different criteria that influence the feasibility of different algal oil production methods. Each criterion consists of different units (e.g. €, kg/m^3, ton DW), therefore it is necessary to standardize the criteria to uniform values between 0 and 1 (with the lowest scoring method receiving a 0 and highest scoring method receiving a 1). Different weights have been given to the current most important criteria based on conditions in the Netherlands, i.e., low irradiation and high land costs. For each criterion the weight and the standardization score have been multiplied, which leads to a final result for each cultivation method.

In the multicriteria analysis the Raceway pond, the Tubular reactor and the Flat panel reactor have been analyzed. The *heterotrophic* cultivation method has been excluded from the analysis for two reasons. First of all due to lack of data on costs, upscaling potential, net energy yield, and other factors. Secondly, heterotrophic cultivation indirectly requires a large amount of energy input, due to the energy needed for the primary production of required organic material (which requires light and other nutrients). Most literature studies included in the state of the art knowledge neglect to include this issue. However, when this energy use is taken into account, with the current state of technology, heterotrophic cultivation would likely not be the most optimal cultivation method for the Netherlands.

Weighing selection criteria

The main criteria that influence algae production in the Netherlands are based on different studies (Brennan 2010, Brennan and Owende 2010, Jorquera *et al.* 2010, Norsker *et al.* 2011) The main criteria identified for this case study are:

(1) costs: investment, maintenance and operational costs. Energy costs are *not* taken into account here.
(2) energy: energy costs. Net Energy Ratio for oil production, biomass concentration
(3) productivity (determined by, e.g. photosynthetic efficiency, biomass density, risk of contamination, stress on algae)
(4) Area needed for production (land use)
(5) future potential: up scale potential, technological improvements

In appendix A an explanation and justification of the chosen criteria and their weights is provided for each criterion.

Table B1 and B2 in appendix B provide the different source data and units used for the multicriteria analysis. For some criteria the state of the art has shown a variation in data for the different algae cultivation methods. In these cases, the results of all available sources have been combined for the standardization (indicated in red in the table). For the criterion 'technological improvements', three sub-criteria were closely related to 'technological improvements' and have therefore been combined in the standardization process (minimum mixing, CO2 available free of cost, production medium available free of cost).
For this case study of production in the Netherlands (high costs of land, lower solar irradiation), based on expert judgment the highest weight has been given to the criterion

'energy input' (30% in total) and 'productivity' (30%). The second highest weighted criteria are 'costs' and 'land use' (15% each), and the third is 'future potential' with 10%.

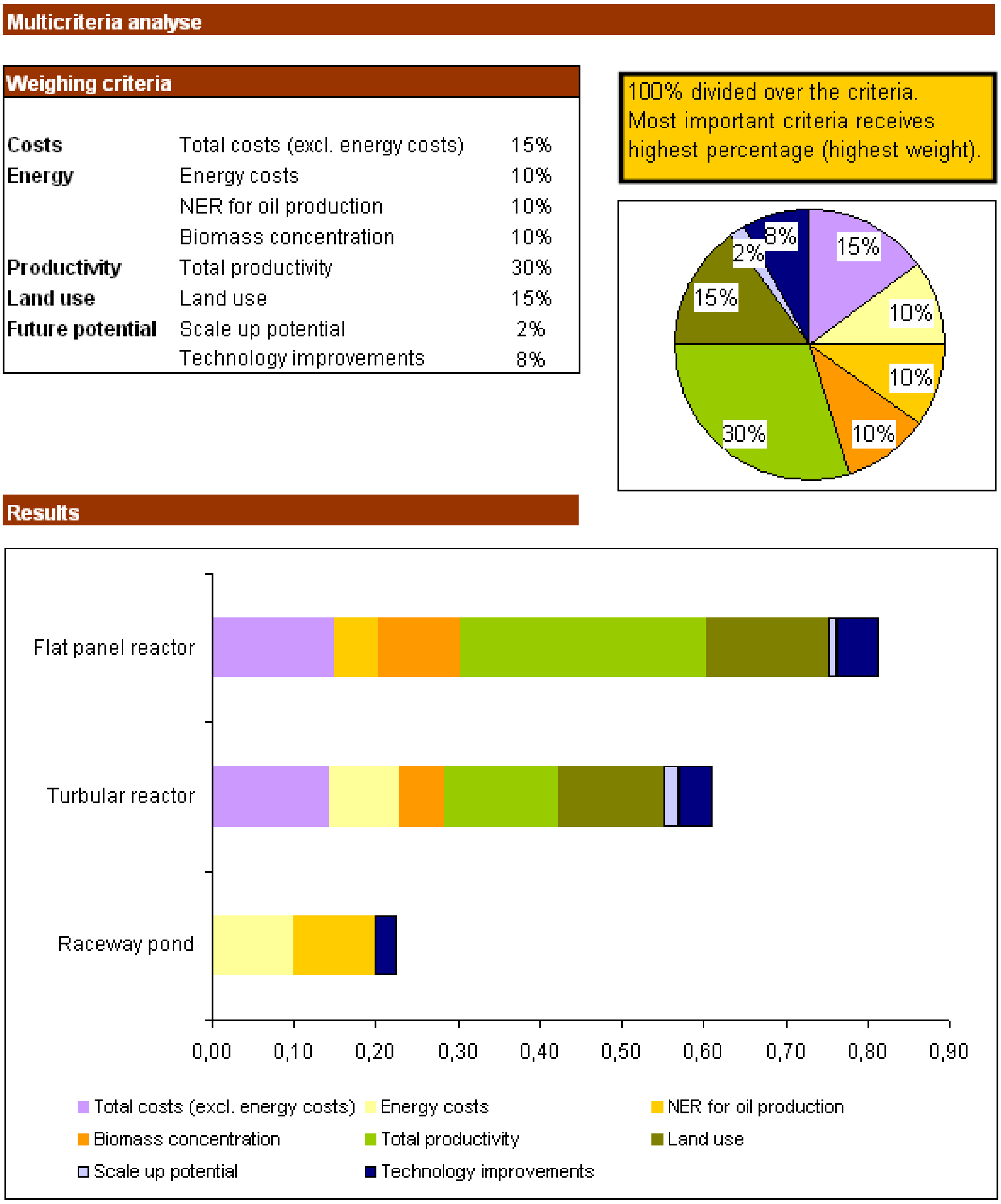

Figure 4.3 Multicriteria analysis overview of results. NER: Net Energy Return. For source of data: Appendix B

Results
The results of the multicriteria analysis (Figure 4.3) show a clear preference for the flat panel reactor for algae production in the Netherlands. Mainly due to the associated high score on productivity, favourable net energy ratio for oil production and relatively low production costs (outside energy costs) the flat panel reactor comes out as the most optimal cultivation method in the Netherlands (considering high cost of land, low solar radiation).

4.3 Potential algae production for kerosene in the Netherlands

The results of the multicriteria analysis show that the most optimal cultivation system for production in the Netherlands is the flat panel reactor. As already discussed, the only feasible processing method is currently the dry method and the algal strain selection has not been analyzed separately, therefore the algae-to-kerosene route selected for this case analysis in the Netherlands can be described as shown in Figure 4.4.

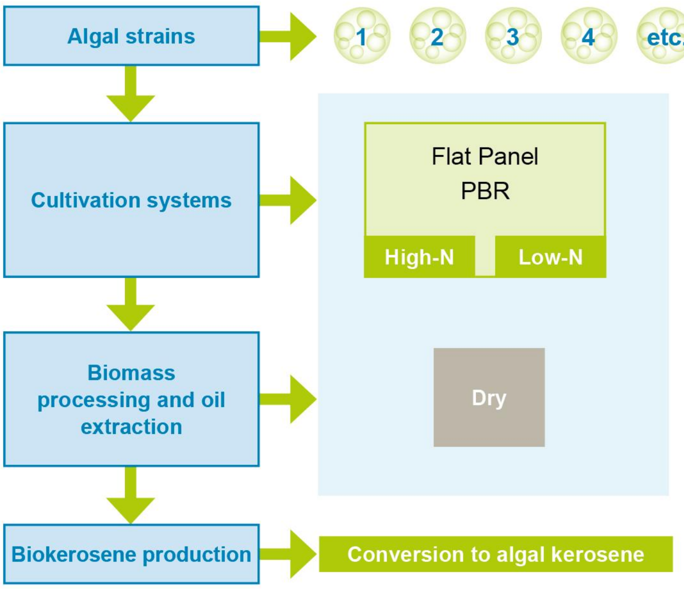

Figure 4.4 Overview of algae-to-kerosene route for flat panel cultivation

According to Norsker *et al.* (2011), the flat panel reactor is able to produce 64 ton DW algae per ha/year. This productivity level is calculated for conditions in the Netherlands -as it is based on a case study in the Netherlands (Eindhoven area)-, thus it has taken into account the limiting factor of low solar radiation in the area.

One kg DW of algae can produce 0.22 litre of algal oil and 0.21 litre of biofuel (Person 2010). This implies that the current production route could potentially produce 64 ton DW X 0.21 = 13,440 litres of biofuel per hectare. This amount is much higher than reported for terrestrial crops in ‘Verkenning lange termijn ontwikkelingen luchtvaart’ (a 2010 document by the Dutch Ministry of Infrastructure and the Environment) which reports production of 1500 litre of biodiesel per hectare. The amount is however lower than the algal biodiesel production reported in Mata *et al.* (2010), who state that even with algae containing 30% oil (low oil content) a production of 64,909 litre biofuel per hectare can be obtained.

The Netherlands has roughly 2,000,000 hectares of agricultural land, of which around 1,850,000 hectares is used for livestock farming and arable land (Statline, CBS 2011). When taking the rough assumption that about 1% of the agricultural land used for livestock farming and arable land could potentially be used for algae production, this would lead to a total production potential in the Netherlands of 18,500 x 64 ton DW = 1,184,000 tons DW algae per year.

To produce 21 litres of biofuel (kerosene), 22 litres of algal oil is needed (Person 2010). From 1 kg dry algae 0.22 litre algae oil can be produced. This would entail a production potential of 248.6 million litres of biofuels annually for the Netherlands (see Table 4.1).

Table 4.1 Conversion ratio's from dry algae to algae oil and biofuels. DW: dry weight. Mln: million.

Dry algae	Algal oil	Biofuel (kerosene)
1 kg DW =	0,22 litre =	0,21 litre
1,184 mln ton DW = 1184 mln kg DW	260,5 mln litre	248,6 mln litre

The current production costs for biofuels using the most optimal production route for the Netherlands is currently not economically viable. Current production costs for the flat panel reactor are €5.96 per kg DW algae (Norsker *et al.* 2011), which is €28.38 per litre of kerosene.

The above gives an indication of the current total production potential of algal kerosene in the Netherlands. Paragraph 4.4 will address to what extent this supply can meet the total demand of the Dutch aviation sector until 2020 and at what costs.

In comparison to the current cost of one litre of kerosene (less than €1 - Verkenning lange termijn ontwikkelingen luchtvaart 2010), the above algal kerosene production cost is very high. It is however important to note that these high costs are partly caused by suboptimal production conditions in the Netherlands, such as high farmland prices and low solar irradiation. In countries where land prices are significantly lower and solar irradiation is optimal, it should be possible to produce algal kerosene at much lower costs. Also, with current R&D developments, the expected increase in cultivation productivity in the following decade could have an important impact on lowering costs. These considerations will be discussed in Chapter 5.

4.4 Demand for kerosene from Dutch aviation sector

In 2009, total fuel used by the aviation sector in the Netherlands was 221.5 million kg kerosene or aviation gasoline (AVGAS). This use is derived from total CO_2 emissions (Klein *et al.* 2011). This amount is based on all flights from Schiphol and other regional airports, including small planes flying on AVGAS. The demand is calculated for the total use of fuel during take-off, landing, approach and flying over Dutch territory. This figure is *not* based on the actual refuelling of airplanes in the Netherlands, nor for the total fuel demand of the main Dutch airline carrier KLM.

To translate current kerosene demand into the future to 2020, two estimated growth rates have been chosen, based on historic compound annual growth rate (cagr). Between 2002-2009, the cagr varied between 1.2% and 2.8%. Also taking into account the current economic downturn and possible recession, demand for 2020 is calculated for conservative growth rates: a very conservative rate of 1% and a less conservative growth rate of 2%.
Based on a 1% cagr, the total demand in 2020 for the Dutch aviation sector could be 247 million kg, which is around **309 million litres**. Considering a 2% cagr the total demand could total 275 million kilo, which translates into **344 million litres** (Figure 4.5).

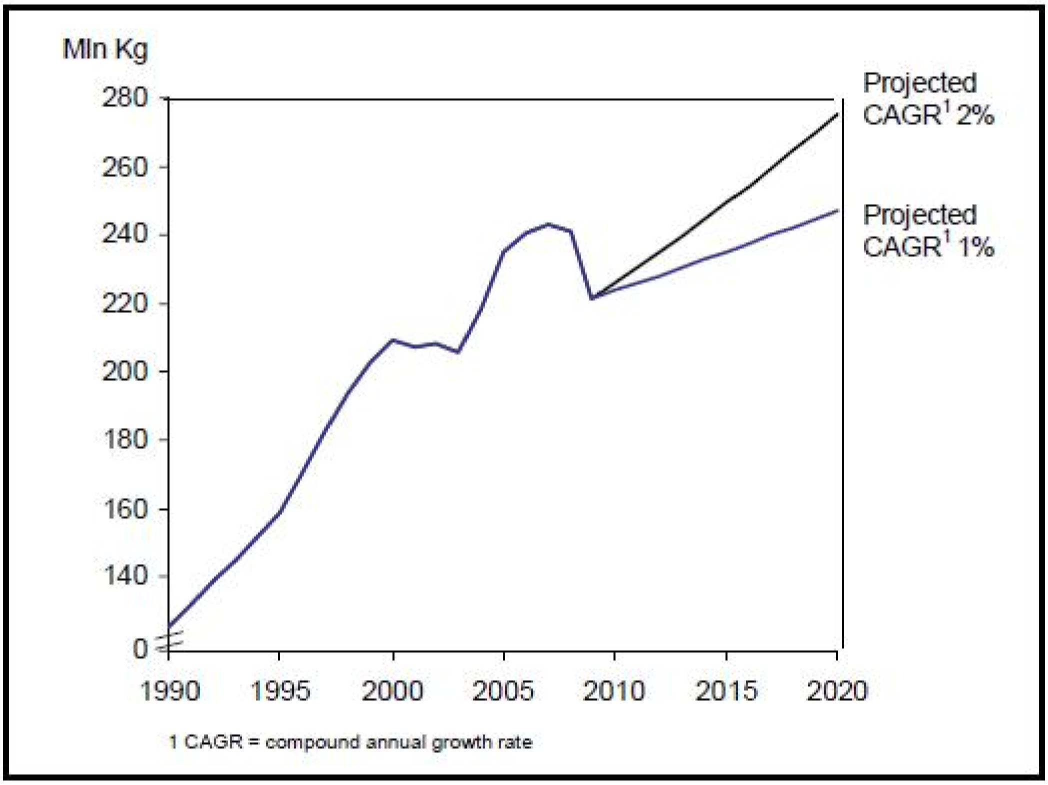

Figure 4.5 Projected kerosene demand for 2 different scenario's

Currently the total demand of the Dutch aviation sector is estimated at 221.5 million kilos, which is around **277 million litres** of kerosene or AVGAS. As analyzed in paragraph 4.3, the hypothetical total algal kerosene production potential based on the availability of land in the Netherlands is **247 million litres** annually. Taken into account that only 50% of the kerosene used in aircraft can be replaced by biofuels, this is 175% of potential current aviation biofuel demand. With the growth projections up to 2020, under the same production conditions, around 140% (higher growth scenario) to 160% (lower growth scenario) of biofuel demand in 2020 could be covered by the potential total algal kerosene production in the Netherlands.

Paragraph 4.3 indicated it is not economically viable to have algal kerosene production at this scale in the Netherlands due to high production costs. However, the above calculation shows the hypothetical order of magnitude of demand that could be covered by the production potential in the Netherlands.

Considerations that influence the economic viability of algal kerosene are algal strain selection, cultivation productivity, technological developments (energy efficiency), nutrient availability, costs and availability of competing fuels, emissions trading developments, and alternative markets for algae products. The next paragraph will touch upon the above considerations, in an attempt to assess the actual future potential for algal kerosene production for the most optimal locations.

4.5 Case study conclusions

4.5.1 Considerations

The above analysis of the Dutch case study is a simplification of the Dutch situation. The actual potential of algae as a source of jet fuel is strongly determined by other aspects not included in our considerations; for instance R&D in the fields of algae production and processing, the cost and availability of alternative fuel sources, and alternative markets for products of algae. We merely estimated the current potential for algal fuel production, based on currently available techniques and available surface area, to serve as a starting point for discussion.

For our multicriteria analyses we have used data from peer-reviewed articles. However, we have found a large variance in data between studies. For example, Norsker *et al.* (2010) report that flat panel photobioreactors have much higher energy demand than tubular photobioreactors, which is mainly due to the use of a blower and paddle wheel, whereas Jorquera *et al.* 2010 states that flat panel photobioreactors have a total energy consumption that is 23 times lower than tubular photobioreactors. When there was a large variation in results between studies, we have chosen to average the values for our multicriteria analysis. However, the energy demand highly influences the net energy ratio. Both energy demand and 'NER' criteria therefore need to be interpreted with caution in our multicriteria analysis to select the 'optimal' method for algal kerosene production.

4.5.2 Conclusions

Could algal kerosene production in the Netherlands theoretically meet the needs of the Dutch aviation sector? At present only a 50 - 50 blend of 50% biokerosene and 50% traditional kerosene is allowed in aviation fuel. Assuming that the production rates estimated by Norsker *et al.* (2010) can be met and when 1% of arable land in the Netherlands is allocated to algae production, then 140 - 175% of the biofuel demand of the aviation industry could be met up until 2020 by the potential production in the Netherlands.
However, the costs of producing one litre of algal kerosene are currently still very high at €28.38 per litre. Furthermore, current cultivation and processing methods have a high energy demand, thereby putting a strain on the net energy ratio.

Although the fuel requirements of the aviation industry could potentially be met by production in the Netherlands, algal kerosene costs and energy demands of algal kerosene production are currently too high to make production feasible. However, it is likely that energy demands and costs will both be significantly reduced with further technological developments in the field of strain selection, cultivation and processing. New technologies such as genetic engineering of the algae and advances in processing algae present opportunities that might make this process sustainable and economically viable in the future.

The following chapter will further discuss the outcome of the state of the art and the case study and its implications for the feasibility of large-scale use of algal kerosene for the Dutch aviation sector.

5 Discussion and Conclusions

In this report we have provided an overview of the state of the art concerning the different phases of algal kerosene production (selection, cultivation, processing), and identified general knowledge gaps and technological bottlenecks. In order to discuss knowledge gaps and bottlenecks specifically for the Dutch situation, a hypothetical case was designed, in which we assessed to what extent algae cultivation in the Netherlands could meet the biofuel demand of the Dutch aviation sector. The case assessed an optimal algae-to-fuel route within Dutch boundary conditions, as the overall feasibility of applying algal kerosene for the Dutch aviation sector is not only highly dependent on the selection of species, methods and processes, but also on the abiotic conditions and economic factors at the location of cultivation.

The hypothetical case of algae cultivation in the Netherlands is based on results and data from the state of the art. The state of the art has however shown a large variation in maximum algae productivity and in energy consumption of the different algae cultivation methods, and an even larger variation in results of different studies conducted worldwide. This variation in results makes it difficult to put great weight on the outcome of the case study; results should therefore be interpreted with caution. The hypothetical case however identifies important bottlenecks for production in the Netherlands and provides a good basis for discussion. We have contacted several Dutch experts in the field of algae cultivation and R&D and we have included their views on the case study and their experiences in this discussion: Prof. dr. ir. Rene Wijffels, drs. Maarten van Dijk and drs. Peter van den Dorpel.

Prof. dr. ir. Rene Wijffels is Professor Agro-technology at WUR and the Initiator of AlgaePARC (see § 2.1.4.3). He holds an MSc in the field of Environmental Technology and a PhD in Bioprocess Engineering, both obtained at Wageningen University. He is Vice President of the Dutch Association of Biotechnology and board member of the International Society of Applied Phycology, European Society of Marine Biotechnology and the editorial boards of the journals Marine Biotechnology and Microbial Biotechnology (www.bpe.wur.nl).

Drs. Maarten van Dijk is a consultant at Spring Associates, focusing on corporate venturing, modelling and due diligence in the sustainability sector. He played an integral part in the introduction of second-generation energy crops in China and the launch of a biomass plantation. He has also been involved in projects such as the development of biofuel strategy for KLM Royal Dutch Airlines. Maarten van Dijk has broad experience in the field of sustainability, technology and business development. He now focuses on project development & business analysis at SkyNRG (see § 2.1.4.1) (www.SkyNRG.com).

Drs. Peter van den Dorpel is the CEO of AlgaeLink (see § 2.1.4.2), which manufactures algae cultivation equipment. He holds a degree in Operations Research and Marketing and has previously worked for GE Plastics with management functions in the field of process operations, technology, sales, marketing and general management. His last function at GE was Managing Director Europe for GE Capital.

5.1 Algal fuel: general potential

Algal kerosene certainly has potential as a jet fuel in the long term. Although properties of algal kerosene and normal kerosene differ slightly, algal kerosene meets the requirements of jet fuel. Aviation infrastructure (e.g. engines) does not need to be adjusted for the use of algal kerosene. Currently, mixing of kerosene and algal kerosene, in a 50/50 mix is allowed and feasible.

Algal kerosene has benefits over traditional fossil fuels in the sense that it does not deplete natural resources. It also has clear benefits over other alternative biofuels in terms of land use and environmental pressure. It has a high photosynthetic efficiency and therefore has a high production per hectare. It can be harvested batch-wise nearly all-year-round, providing a reliable and continuous supply of oil. Its ability to be cultivated in saline water is unique.

Production of algal kerosene is however currently underdeveloped and too expensive to compete with traditional fossil fuels. It is not yet economically feasible to produce algal fuel commercially for the aviation sector.

With R&D efforts and developments going towards upscaled installations, the cultivation and processing costs are expected to decrease significantly, to the extent that algal kerosene could become an interesting cost-effective and sustainable alternative aviation fuel. However, the extent of R&D efforts is much dependent on European and (inter)national renewable energy policies, the application and costs of ‘competing’ renewables and alternative (niche) markets for algae products.

> *“With less available fossil fuels, it is necessary to explore alternative fuels to keep the economy running. The end-users must look for alternatives; this will increase opportunities for algal fuels. […] Other biofuels [than algal fuel] are however not a real durable solution to entirely replace traditional fuels with. Cooking oil is not sufficiently available, and requires a lot of effort to process. Palm oil and jatropha production leads to conflicts with land-users and the environment. These conflicts are not or barely applicable with algal production: a much smaller surface is required, and no fertile agricultural land.”* – Wijffels.

There is little experience with upscaling of algae cultivation installations and the pace and extent of technological developments in the sector is unclear. Therefore, it would be highly speculative to indicate when (at which production level, at which oil price) algal kerosene production will become economically feasible. Experts indicate that commercial production will probably only take off in ten years, if important bottlenecks are overcome in R&D programmes, and production routes focus on multiple end-products.

> *“It is too early to indicate which production systems are most promising, that would be speculating. This has also been told to the participating industries [in the AlgaePARC consortium]: it will take approximately 5 years to develop a commercially viable business case for energy production. The execution and up scaling to a full commercial process could however take 10 to 15 years.”* – Wijffels.

> Van Dijk agrees: “*The potential of algae as a source of fuel is too big to ignore, but we are very aware that algal fuel is not the solution for the next 1, 2 or 10 years. This is as long as it will last before there is sufficient algae production so that alternative food/feed markets are saturated and [low valued] jet fuel gets its turn.”*

> Van den Dorpel is more optimistic: *“With economies of scale and more efficient harvesting and drying methods, the market for low value commodities will be increasingly accessible. Depending on the oil price and international focus on renewables,*

commercial application of algal kerosene can be viable within 1-5 years, purely through cost reductions and technological developments."

Niche markets display strong demand for specific products which can already be viably produced from algae. Production of PUFA's (poly unsaturated fatty acids) as well as anti oxidants by microalgae seem most promising in the short term as current production costs are compatible with market demand. Though this demand may trigger the development of new producers of microalgae, it may also provide an obstacle for large-scale production of algal biomass specifically for the benefit of algal kerosene production.

Wijffels is optimistic: "These days our [algae production] sector does also focus on commodities, bulk markets. There is a large industrial demand for commodities, basic materials. Biokerosene is currently depending strongly on palm oil production, and the industry is now searching for alternatives. There is a strong driver for algae research focused on biofuel."

However, Van Dijk indicates: *"Every producer of algal biomass will first deliver his highly valuable products to the food/feed market. Only when these markets are saturated, they will produce for the less profitable commodities market. Also, there is a price competition with other bio-oils; the cost price of soy and palm oil is significantly lower."'*

Van den Dorpel agrees: *"In the short term, entrepreneurs will opt to produce for profitable markets such as food/feed. This is a normal market phenomenon. Unless governments identify algal fuel as a priority topic, and decide to stimulate this sector through subsidies."*

The experts we interviewed identified the same bottlenecks for large-scale commercial production of algal fuels as mentioned in chapter 3, which are optimal strain selection and genetic engineering, energy consumption from water pumping and mixing, nutrient use and recycling, lack of experience with up scaling, and extraction of oil from algae. These bottlenecks will be addressed in the following sections.

5.1.1 Algal strain selection

Many different algal species are currently being used in algae cultivation for fuel production, all with different intrinsic characteristics. R&D in this field is strongly developing, likewise in the field of genetic modification. The selection of species to be used for algal kerosene production depends on various factors: species traits and productivity, tolerance to changes in temperature, and capability to cope with stress. It is therefore not easy to identify 'the optimal' algal species for algal kerosene production overall. Genetic engineering and metabolic engineering are seen as options to eventually develop an 'ideal' strain that has all desired traits concurrently.

"Genetic/metabolic engineering research focuses on the efficiency with which oil is accumulated in algae, on the increase of oil yield with light intensities, and excretion of oil. There is not too much research being done in the field of genetic engineering, but it is certainly an important focus area for industrial R&D. Craig Venter and Exxon Mobil are leaders in this field." – Wijffels.

A research program by Craig Venter (the first mapper of the human genome and creator of the first synthetic cell) and Exxon Mobile has searched for a naturally occurring algal strain that can be converted into a commercial-scale biofuel. However, they have not found such a strain. Exxon Mobil and Venter continue to attempt to manipulate natural algae, but are now starting to believe the answer lies in a fully synthetic cell approach (Foreign Policy 2011).

5.1.2 Cultivation methods

Four main algae cultivation methods have been described: two types of photobioreactors (PBRs), tubular photobioreactors and flat panel photobioreactors, the raceway pond, and the heterotrophic cultivation. Heterotrophic production is a fast way to produce lipids. However, since it requires sugar as source of energy, it is not an efficient way to convert light into energy. The potential of heterotrophic production becoming sustainable in the future is rather low.

> Wijffels on heterotrophic cultivation: *"At this moment, heterotrophic production is the faster way to produce lipids. A down side is that it requires sugar, similar to ethanol production, which makes it very hard to ensure a sustainable production process. But if you would like to bring algae products to the commercial market fast, heterotrophic production is a good solution. On the larger scale, it is however not feasible, due to the large glucose requirements. This could be solved through the use of hemicellulose, but in bio-ethanol this is also not yet a feasible option."*

> Van Dijk strongly disagrees: *"Heterotrophic cultivation should have been included in the case study. This method has a lot of potential, as conversion is more efficient. For this cultivation method, a lot can be learnt from the ethanol industry, which can almost produce at a cost competitive level. It is already possible to buy algal kerosene off Solazyme for 30-35USD per gallon - from heterotrophic cultivation.*"

Although it is true that Solazyme's heterotrophic production system is nowadays the only system that commercially delivers algal jet fuel to aviation companies, we believe that the sugar production required for upscaling heterotrophic cultivation, will have a significant negative impact on water resources and on the availability of agricultural land. This cultivation method is therefore in the long run less suitable.

The other three different cultivation systems each have their beneficial aspects (raceway ponds are generally cheaper than PBRs), but also their drawbacks (raceway ponds are more sensitive to contamination and require a larger land area). The weight of their benefits and drawbacks is strongly dependent on location, since land cost and availability, solar radiation and level of technology infrastructure varies widely across the world.
There are several important criteria on which an optimal cultivation system should be selected, such as productivity, energy requirements, risk of contamination, possible by-products, as well as operational and maintenance costs.

The current available production systems are not yet productive and efficient enough to perform large-scale production commercially. Based on current knowledge and experience from experimental and pilot studies it is also not yet possible to select one optimal cultivation method. R&D is ongoing; according to experts it should be possible to identify an optimal cultivation method within 5 years.

> Van Dijk warns*: "It is not realistic to base yield estimates analyses on scientific and experimental studies. In all other alternative energy crops that have been examined,*

> *such data has proven to be inaccurate or false. Only up scaled commercial production systems can provide reliable data."*

Van Dijk's warning is valid. Reliable production yield data from larger scale producers has proven to be hard to access for our evaluation. Such data could certainly enable more accurate analyses.

Efficient nutrient use and recycling
Nutrient availability does seem to become an issue with up scaling of cultivation systems; very large amounts of phosphorus, nitrogen and carbon dioxide are required, which is bound to put a pressure on the environment (similar to fertilizers in agriculture).
Nutrient recycling will therefore become essential for cost-effective and sustainable up scaling. As nutrient recycling is currently not yet feasible in available processing methods, this will most likely become a main R&D topic in the field of processing. This field of research could ultimately work towards stand-alone systems: the ultimate aim would be to design a cultivation system that is independent of the supply of nutrients. Such stand-alone systems could be possible as algae contain nitrogen and phosphate, but the oil harvested from algae does not. There are, however, limitations to internal nutrient recycling due to transformation of elements into refractory forms.

> R. Wijffels indicates: *"When it comes to nutrient requirements, phosphorus plays an important role. AlgaePARC examines residual flows, for carbon dioxide, phosphorus and nitrogen. We examine nutrient recycling on a large-scale, but we also examine how to make systems independent of nutrient inputs."*

Effective nutrient recycling will however reduce the possibilities for the extraction of by-products: all substances that are recycled back into the system cannot be extracted as a by-product.

It is therefore essential to make optimal use of waste streams (e.g. nutrients, CO_2 and heat) from other industries and wastewater treatment plants.

> Van den Dorpel even comments: *"Cultivation of algae should always be connected to waste streams: making use of waste water, waste heat and carbon dioxide is necessary to be cost-effective. From waste water and waste streams from the food/feed industry, enormous amounts of* CO_2 *and nitrate/phosphate are available, that require minimal processing before use. To make optimal use of these waste streams, production will always have to take place on a co-location with another industry."*

Energy consumption from pumping, mixing and harvesting
Norsker *et al.* (2011) identified the dominant factors influencing costs of algal oil production to be irradiation conditions, mixing, photosynthetic efficiency of systems, medium and carbon dioxide costs. Extracting interesting molecules such as the oils without damaging microalgae is one of the techniques which could allow continuous production, increasing production yield.

> Wijffels indicates: *"The most energy demanding components of algae cultivation are pumping and mixing water. In these fields, the biggest improvements can be made. The costs need to be reduced by 90%, but several developments are required at the same time in order to reach a feasible, cost-effective system.."*

"It is important to use as little water as possible, so that pumping is limited to a minimum. This also has benefits with harvesting algae: the algal biomass will occur in higher densities in the medium." – Wijffels.

Currently, four technologies are aiming at concentrating the algae (flotation, sedimentation, filtration, centrifugation), none of which seem to be achieving adequate yields at acceptable costs (essentially energy costs) for large-scale productions.

Van Dijk underlines this: *"A lot of attention should be given to harvesting of algae, as this requires enormous amounts of energy and strongly determines the production costs. Now harvesting is being done predominantly through centrifuging, but this is not financially feasible."*

Upscaling of cultivation
In the field of algae cultivation, there is little experience with upscaling; most cultivation systems worldwide and all cultivation systems in the Netherlands are on a small, experimental scale.

Upscaling of PBRs could lead to several technological issues: lower light dispersion, micro-fouling, additional CO_2 supply, and loss of heath with increased size PBR, which would require more pumping. However, interviewees indicate that the negative impact of these issues is limited:

"Indeed, it is likely that production costs will decrease with upscaling, but it all depends on the level of upscaling. The investments of a cultivation system are not so high that up scaling is only cost-effective with enormous proportions. The cost-price is not likely to decrease much with installations larger than 500 hectares. The limiting factors will not become bigger issues with upscaling, as you work with independent, repetitive cultivation modules." - Wijffels

Van den Dorpel agrees: *"Upscaling will not lead to a lot of problems; systems are modular. The most important obstacle for upscaling is lack of project funding."*

The use of modular cultivation systems seems to be an effective approach to prevent upscaling obstacles.

5.1.3 Processing

Processing appears to be one of the most important factors determining the total energy budget and also the total costs of algal kerosene production (Lardon 2009, Norsker *et al.* 2011, Xu *et al.* 2011)
Much R&D work has been done on processing technologies. The dry processing method is the method most widely used, while wet processing is in its infancy and currently very expensive. Even though the dry processing method is currently the only feasible processing method, this method does not allow for nutrient recovery. If this problem is not overcome, it will put severe pressure on the nutrients available in the world when upscaling algae production. As a consequence of the high nutrient demands associated with algal cultivation, nutrient recovery is a prerequisite for producing large quantities of algal kerosene.
It is likely that the (expected) benefits of wet processing (nutrient recycling, reduced energy demand for drying the algal slurry) will lead to an increased focus on R&D on this alternative method. Development of effective wet processing technologies could lead to large changes in

the algal kerosene production process in terms of input and costs. It is however difficult to indicate how fast these developments will occur, what the ultimate potential of wet processing will be, and how much processing costs and energy demand could ultimately be reduced. Also, efficiency of hydroprocessing methods for algae has not been widely described.

> Van Dijk correctly warns: *"In the case study, data has been used for conversion of algal oil to biodiesel. This leads to an overestimation of the yield. Also, you have not taken into account that kerosene production has a no more than 70% efficiency. Conversion from algal oil to algal kerosene, under hydropressure, is probably half as efficient as conversion to biodiesel. Conversion to algal kerosene is significantly more expensive, maybe with a factor 5-10, and also requires significant investments in larger factories. We now work with €200-400 for conversion of one ton of algal oil to kerosene. This could probably be reduced with €200 over the next 3 – 5 years."*

The other interviewees agree on this potential leap in efficiency and cost-reduction in the processing stage:

> *"When it comes to oil extraction processes, the wet route is ultimately the only feasible route, in which the biomass does not need to be dried (as much) prior to extraction. This saves quite some energy. A lot of work is required in the field of extraction; research now focuses on how to break cell walls in milder enzymatic or mechanical ways."* - Wijffels.

> *"The largest steps towards economic feasibility can be made through improving the efficiency of downstream processes: extraction, harvesting, drying processes. Wet processing is a very promising development; existing techniques from the food processing and water purification sector are combined to come to a processing method in which less drying is required."* - Van den Dorpel.

5.2 Concluding remarks

5.2.1 Algae cultivation is not optimal in the Netherlands

Theoretically, it could be possible to produce sufficient algal kerosene in the Netherlands to meet the demand of the Dutch aviation sector (if 50/50 biofuels are used), when 1% of agricultural land is used for algal oil production. However, as cultivation and processing costs are very high, this is currently not economically feasible compared to using traditional fossil jet fuels. With relatively low availability of land, high land costs and very low solar irradiation, it would not presently be advisable to perform large-scale cultivation in the Netherlands. Moreover, by producing algae in the Netherlands, one of the benefits of algae production, i.e. production does not have to take place on arable land, would be lost. Producing algal kerosene can best be done in an environment with high solar irradiation; resulting in a higher productivity at the same costs.

> *"Optimal locations for production are those with a stable climate; with stabile temperature and light regimes. Currently our best yields are observed in North Eastern Australia; a lot of sun and not a lot of extremes."* - Van den Dorpel.

Relocation of production and processing further away from air traffic hubs like Schiphol Airport could possibly lead to an increase in transportation costs.

> Wijffels however states: *"Availability of water and nutrients are most essential for selecting an optimal location for large-scale cultivation of algae. Transport is not likely to be a large issue; production somewhere close to Schiphol does not necessarily have a very big added value."*

> Van den Dorpel adds: *"Algae cultivation activities of course benefit from basic forms of infrastructure and logistics; it helps being in the vicinity of coastlines or near harbours. This is not extremely important though, the cultivation systems and required logistics are not very complicated."*

However, technological infrastructure and local capacity to control and maintain an algae culture might not have equal standards everywhere. Water and nutrient availability could also be limiting factors for selecting a location. These aspects should be taken into account when deciding on an alternative location to produce algal kerosene.

> Wijffels comments: *"Initially, experimental cultivation is taking place in the Netherlands, but for up scaling, cultivation needs to be relocated to locations with optimal irradiation, temperature, and availability of water and residual streams (nutrients, carbon dioxide)."*

> Van den Dorpel also indicates: "*It is likely that algae production will take off most in Asia, where there is most funding capital and commitment from the food/feed industries. The US are very determined and active in the field of fuel, a lot of developments are to be expected there."*

This could however constitute to limit potential R&D progresses: the northern part of Europe is expected to be handicapped compared to countries with higher irradiation or countries with a strong political or market push towards algae production. It would therefore be advisable to support long term R&D initiatives (through focusing on experimental setups) in the Netherlands, to retain a leading knowledge position in the European algae sector.

5.2.2 Production cascade: multiple end products have the highest potential

There is a growing demand for products that can be made cost-effectively through algae production pathways such as Omega-3 or Omega-6 fatty acids, proteins, amino-acids and anti oxidants. In this view, it is likely that algae will be used as precursors for multiple products (i.e., the concept of a bio refinery) from cosmetic additives to energy feedstocks. Under the Dutch Energy Research Programme (EOS), the AlgiCoat project (a collaboration between WUR, Akzo Nobel, Essent and Ingrepro) different possible cascades are being designed. The first being the production of high value chemical coating components together with lower valued biofuels, and waste stream biomass.

> Van den Dorpel indicates: "*A cascade of products is required for economic reasons; selling multiple products when going down the value pyramid. It is also a method to get 'rid' of waste products (algal cake) in a cost-effective way."*

> Van Dijk is even more explicit: *"Algae cultivation will always need to be connected to waste streams: making use of wastewater, rest warmth and CO_2 is simply necessary to*

be cost-effective. And even then, a cascade of products is required to reach economic feasibility of algae production."

Wijffels agrees: *"Ultimately, the feasible business case for algae production will probably show a combination of end products. Lipids are important end products, but also proteins and amino acids are important; proteins are of great use in the food/feed industry, amino acids in the chemical industry. In the case of such by-products (next to algal oil), nutrient recycling is not or hardly possible. There is not really one solution, one optimal production route; several combinations of solutions are possible. Cooperation with different industries (as happens now in AlgaePARC) is required to develop integrated optimal solutions"*

5.2.3 International, multi-disciplinary, integrated and long-term: the way to go

Lack of knowledge-sharing between international institutes or companies may lead to an overall slow learning process, which could hamper knowledge development in this sector significantly. It is therefore essential to support international research programmes.

"With this type of [commodities and energy] problems, it is necessary to look beyond country borders. Provision of alternative fuels and raw materials is not merely a Dutch problem; we shouldn't want to solve this by ourselves. International cooperation is required." - Wijffels

Major technological developments have been supported by the biotechnology sector, allowing microalgae producers access to well established technologies. Initiatives such as AlgaePARC are good examples of R&D efforts that focus on overcoming various bottlenecks in multidisciplinary teams, with strong involvement and cooperation of the commercial industries, which are ultimately end-users of the various products that can be made from algae.
Demonstrator projects are essential to show end-users and financers the state and prospects of R&D developments. Several demonstrator projects are executed through the FP7 Energy Call (FP7 ENERGY.2010.3.4-1), evaluating the potential of microalgae to produce biofuel. The major technologies for microalgae cultivation and processing for algal kerosene can also benefit strongly from technological developments in the chemistry, chemical engineering and biotechnology sectors.

"Algae cultivation generally receives a lot of attention nationally and internationally; however this does not directly result in larger R&D programmes. It would be good to provide financial support for multi-disciplinary programmes with a long term agenda (such as AlgaePARC), in order to retain this focus over the next 10, 15 years. In the next 5 to 10 years, several go/no go moments will take place. How feasible these various cultivation systems will be, depends on how far the research has advanced, but also on the economic situation." - Wijffels

Van den Dorpel suggests: *"Governments and industries should focus on integrated biobased economy projects. The concept of Biobased Economy is an important vehicle to stimulate algae production. Integrating agricultural waste streams in algae production creates an array of opportunities."*

5.2.4 Patience and endurance are required

Policies that stimulate renewable energy production and consumption, increasing costs of GHG emission rights, and increasing prices of traditional fuels will have a stimulating effect on the biofuel market as a whole, paving the way for algal fuels.
However, for algal kerosene to reach full commercial application, it is necessary to avoid a second 'boom and bust' cycle: microalgae developments were high on the agenda during the 1980s before an almost complete blackout during the 1990s. The rather recent resurgence in interest can be a potential risk: if current biofuel demonstration projects are not achieving their objectives, the negative signal sent to investors might divert funding from the sector.

> Wijffels agrees: *"The largest bottleneck is probably to bridge the coming period; most probably in the next 10 to 15 years technology developments will take place so that large-scale cultivation could certainly be executed cost-effectively. This however requires patience and endurance from involved stakeholders; producers, researchers* and *investors."*

5.3 Recommendations

While algae feedstocks for kerosene production are not economically competitive with fossil fuels at the present time, algae are a promising source of kerosene in the long run. The fact that algae cultivation does not require arable land and only a limited amount of freshwater justifies attention to algal biofuels from researchers, industries and policy makers (IEA Bioenergy Task 39 2011).

Even when large-scale cultivation of algae is likely to be realized faster in regions like Australia, Asia or the US (either due to favourable local circumstances, strong market pull (e.g. food/feed market) or strong government push (e.g. concerning energy requirements), respectively, it will still be important for the Dutch algae sector to retain their focus and activities in this field. Rather than the actual production of algal oil or algal kerosene, Dutch innovative ideas and technologies in the field of cultivation and processing can be seen as valuable export products. The Netherlands is now one of the leading countries in Europe in the field of algae biotechnology, mainly due to large-scale multi-stakeholder R&D initiatives such as AlgaePARC and a strong involvement of multinationals in the food technology sector. In order to maintain this knowledge position of the Netherlands, the Dutch algae sector, both research and technology, needs to be strengthened, to keep up with developments in other regions.

The R&D developments in the Dutch algae sector are strongly dependent on a market pull, which should lead to an effective demand-driven process. However, a government push is regarded essential to support and motivate innovative research and possible high-risk entrepreneurship.
The level of government push by the Dutch government would of course depend on prices of fossil fuels and alternative biofuels on the one hand, and (international) political developments and corresponding effort requirements in the field of sustainability and CO_2 emissions on the other. Regardless of the extent or the type of government support to the algae sector, the Dutch government should however demonstrate a persistent, long-term focus on integrated, multidisciplinary and *international* R&D programs, also to enable an effective response of the Dutch sector to international R&D developments in other regions. These programs should not necessarily focus merely on algae for biofuels, as the possibly faster developments in the

algae for food/feed/chemicals markets may lead to an enormous boost to the algae cultivation sector as a whole, which will definitely benefit algal biofuels production.

The Dutch government has an important role in bridging the time needed to optimize algal fuel production technologies required for commercial utilization of this potentially highly sustainable source of biofuel in the future.

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A Criteria and weights

A selection of criteria has been used in the multicriteria analysis. The total weight of all criteria is 100%. The following graph gives an overview of the different weights (Figure A.1). The choice of criteria and the justification and reasoning behind the weight given per criterion is explained.

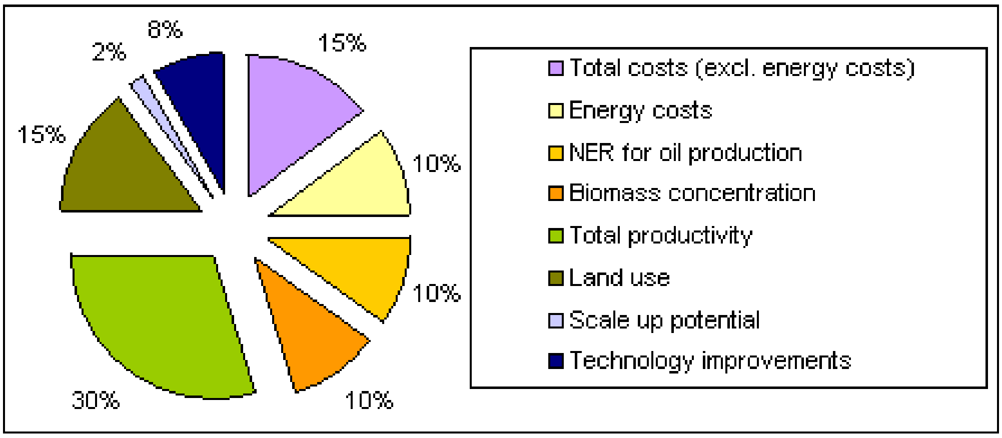

Figure A.1 Weighting criteria and their weights of the executed multicriteria analysis.

Costs: This criterion entails the total costs per cultivation method excluding energy costs. The different sub-criteria are: Investment, maintenance and operation costs (again excluding energy costs). Evidently, this is an important criterion as it determines whether production is economically viable. For this reason a weight of 15% has been given to this criterion.

Energy: As energy output is a very important criterion for the success rate of biofuels, it is taken as a separate criterion consisting of three sub-criteria: Energy cost, Net Energy Ratio (NER) for oil production and also biomass concentration as this highly influences the energy needed to process algae. All three sub-criteria have been given a weight of 10%; thus a total of 30% for energy, to underline the significance of this criterion for algal kerosene development.

Productivity: The criterion productivity is determined by e.g. photosynthetic efficiency, biomass density, risk of contamination and algae stress. As the productivity rate determines the most successful cultivation method, it was considered as one of the most important criteria. Therefore it is weighted at 30% in the analysis.

Land Use: This consists of the required land-use for production. There is a negative correlation between the amount of land necessary to produce 1 litre algal oil and the score in the multicriteria analysis. As this is a very important issue/constraint particularly for production in the Netherlands, this criterion is weighted at 15%

Future potential: This criterion assesses the upscaling potential and the expected technological improvements. These sub-criteria together have been given a weight of 10%, as we consider it to be important. However due to high uncertainties it has not been given a higher weight.

B Data used in multicriteria analysis

Table B.1 Data and units per criterion for three different cultivation systems

Category	Criteria	unit	positive or negative criteria	Raceway pond	Turbular reactor	Flat panel reactor	REF
Cost	Total costs (excl. energy cost)	€	negative	4,64	3,58	3,52	(a)
Energy	Energy costs	€	negative	0,27	0,58	2,44	(a)
	NER* for oil production (2)	ratio	positive	3,05	0,07	1,65	(b)
	Biomass concentration (1)	kg/m3	positive	0,32	1,70	2,01	(a)
	Biomass concentration (2)	kg/m3	positive	0,35	1,02	2,70	(b)
Productivity	Total productivity	ton DW per ha/year	positive	21,00	41,00	64,00	(a)
Land use	Land use required	% tov Raceway pond	negative	100,00	50,00	33,33	(a)
	Space required for biomass production of 100,000 kg/year (m2)	km2	negative	25,99	10,76	10,15	(b)
Future potential	Scale up potential of cultivation system	ratio	positive	0,00	1,00	0,50	(a), (c)
	Minimum mixing	% decrease production costs	positive	0,00	0,26	0,48	(b)
	CO2 free (in addition to minimum mixing)	% decrease production costs	positive	0,16	0,11	0,11	(b)
	Medium free (in addition to CO2 free + minimum mixing)	% decrease production costs	positive	0,10	0,16	0,16	(b)

(a) Norsker *et al.* (2011)
(b) Jorquera (2010)
(c) Brennan (2010)

Table B.2 Results standardized per criterion

Categories	Standardization Criteria	Maximum	Minimum	Raceway pond	Turbular reactor	Flat panel reactor
Cost	Total costs (excl. energy cost)	4,64	3,55	0,00	0,97	1,00
Energy	Energy costs	2,44	0,27	1,00	0,86	0,00
	NER for oil production	3,05	0,07	1,00	0,00	0,53
	Biomass concentration (1)	2,01	0,32	0,00	0,82	1,00
	Biomass concentration (2)	2,70	0,35	0,00	0,29	1,00
	Total biomass concentration			0,00	0,55	1,00
Productivity	Total productivity	64,00	21,00	0,00	0,47	1,00
Land use	Land use required	100,00	33,33	0,00	0,75	1,00
	Space required for biomass production of 100,000 kg/year (m2)	25,99	10,15	0,00	0,96	1,00
	Total land use			0,00	0,86	1,00
Future potential	Scale up potential of cultivation system	1,00	0,00	0,00	1,00	0,50
	Minimum mixing	0,48	0,00	0,00	0,55	1,00
	CO2 free (in addition to minimum mixing)	0,16	0,11	1,00	0,02	0,00
	Medium free (in addition to CO2 free + minimum mixing)	0,16	0,10	0,00	1,00	0,98
	Total technology improvements			0,33	0,52	0,66