Algae as a source of fuel for the Dutch aviation sector – a feasibility study

Executive 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 document is a summary of the executed study and 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)?

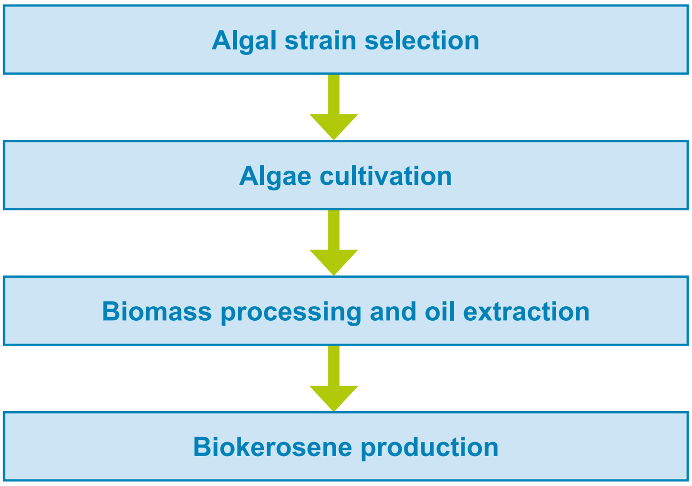

Figure A. A simplified schematic overview of the algal kerosene production proces

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.

Algae cultivation

There are several cultivation systems, of which we have taken the four most common into account 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

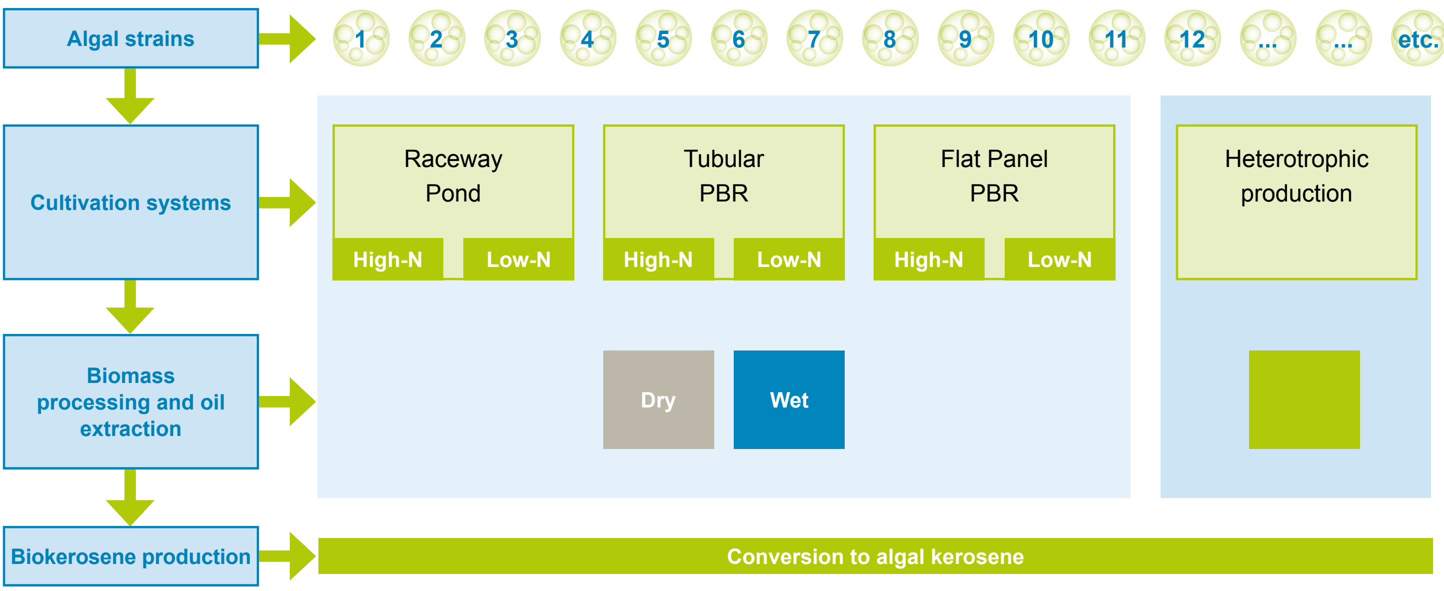

Figure B. A simplified schematic overview of the different ways to produce algal kerosene

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).

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 netto 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.

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 due to the high latitude 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, biodiesel is not optimal for use in the aviation sector as components in the fuel could solidify at low temperatures. Biokerosene 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.

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:

- selecting and/or modifying algal species with optimal traits
- optimizing pumping systems, so less energy is needed to provide nutrients and CO_2 to the culture
- 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.

References

ATAG, *Air Transportation Group*, Geneva. (2009)

Brennan, L., and Owende, P., *Renewable and Sustainable Energy Reviews* 14:557-577. (2010)

Chen, G. Q. and Chen, F., *Biotechnology Letters* 28:607-616. (2006)

Chisti, Y., *Biotechnology Advances* 25:294-306. (2007)

Demirbas, A. and Fatih Demirbas. M., *Energy Conversion and Management* 52:163-170. (2011)

Jorquera, O., Kiperstok, A., Sales, E. A., Embiruçu, M. and Ghirardi, M. L., *Bioresource Technology* 101:1406–1413. (2010)

Lapuerta, M., Armas, O. and Rodríuez-Fernández, J., *Progress in Energy and Combustion Science* 34:198-223. (2008)

Lardon, L., Hélias, A., Sialve, B., Steyer, J.-P. and Bernard, O., *Environmental science & technology* 43:6475-6482. (2009)

Mata, T. M., Martins, A. A. and Caetano, N. S., *Renewable and Sustainable Energy Reviews* 14:217-232. (2010)

Miao, X. and Wu, Q., *Bioresource Technology* 97:841-846. (2006)

Norsker, N.-H., Barbosa, M. J., Vermuë, M. H., and Wijffels, R. H., *Biotechnology Advances* 29:24-27. (2011)

Person, J., *Trimatec*, France. (2010)

Wijffels, R. H. and Barbosa, M. J., *Science* 329:796-799. (2010)

Xu, L., Brilman, D. W. F., Withag, J. A. M., Brem, G. and Kersten, S., *Bioresource Technology* 102:5113-5122. (2011)

Xue, J., Grift, T. E. and Hansen, A. C., *Renewable and Sustainable Energy Reviews* 15:1098-1116. (2011)

Selection of most used references. Extended reference list can be found in the report.

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.

You can download the full report on **www.kennisonline.deltares.nl**

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