MICROALGAE – OPPORTUNITIES AND CHALLENGES OF AN INNOVATIVE ENERGY SOURCE

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ABSTRACT: Microalgae produce higher biomass and oil yields than traditional energy crops, and they can be cultivated on marginal land or in seawater. Additional benefits can be achieved from co-production of food, feed and high-value chemicals as well as from environmental services, such as bio-fixation of CO_2 and wastewater treatment. However, biotechnical, environmental, and economic challenges need to be overcome before large-scale production of algal-based biofuels becomes economically feasible. Major bottlenecks are high cultivation and harvesting costs, unfavourable energy balances, and the demand of nutrients. Long-term R&D in biotechnology is needed to develop systems for the production of sustainable algal-based biofuels. Moreover, the availability of land and nutrients for mass algae cultivation should be assessed and suitable production sites identified.

Keywords: algae, technology, environmental impacts, economics

1 INTRODUCTION

Predictions that crude oil prices will reach highs of 150-200 $ per barrel and rapid food price hikes in 2008, which the World Bank attributed to the production of biofuels, have renewed attention to algae. They offer an alternative biomass source which could solve the fuel-for-food dilemma and the environmental problems which constraint 1st and 2nd generation biofuels. Hence, algal-based biofuels are assumed to be the '3rd generation' biofuels. Research in microalgae for energy production is conducted worldwide, in public institutions and private companies. Notably airlines have interest in algal-based kerosene-grade fuel due to the commitment of the International Air Transport Association to 'carbon neutral growth' by 2020 and to apply 10% alternative fuels by 2017 [1, 2].

Autotrophic algae are relatively simple plant-like organisms that capture light energy through photosynthesis and use it to convert inorganic substances (water, carbon dioxide, nutrients) into organic matter and store the trapped energy as some form of carbohydrates. Algae are a diverse group of aquatic organisms and depending on the species they can produce different feedstock for energy generation [3]:

- lipids for biodiesel and jet fuel production,
- carbohydrates for ethanol production,
- hydrocarbons and isoprenoids for gasoline production, and
- hydrogen (by direct synthesis in microalgae).

Beyond that, the complete algal biomass can be processed for energy production. The different energy conversion paths for algal biomass include (Figure 1):

- gasification for syngas and BtL-production,
- hydrothermal gasification for hydrogen production,
- methane production by anaerobic digestion, and
- co-combustion for electricity production.

However, not all of these energy conversion processes can be applied efficiently to microalgae due to their characteristics, e.g their high content of water, nitrogen and phosphorus compared to traditional energy crops. Direct combustion of microalgae for example is only feasible if waste heat is available for drying.

Microalgae can also be used as substrate for bio-refineries and to synthesize high-value co-products for the food, feed or chemical industry. Besides, they can be used for environmental services, such as CO_2-recycling from power plants fired with fossil fuels and for wastewater treatment.

Microalgae are currently not used commercially for energy production, but have several applications from human and animal nutrition to cosmetics and the production of high-value products (e.g., pigments, antioxidants, and polyunsaturated fatty acids). The worldwide annual production of algal biomass is estimated to be 5,000 Mg of dry matter with a market value between 200 and 2,000 € per kilogram [4].

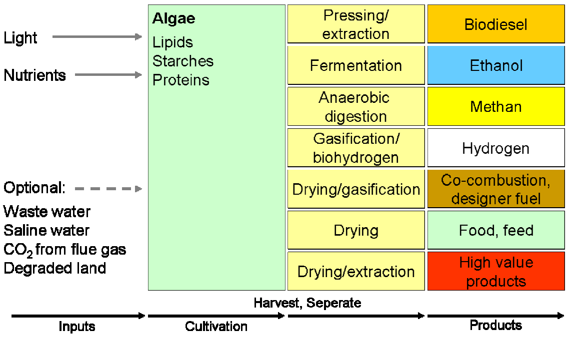

Figure 1: Energy production by microalgae

The objective of this paper is to give an overview on the opportunities and the biotechnical, ecological, and economic challenges of large-scale microalgae cultivation for energy production. In doing so the focus is on microalgae – in contrast to macroalgae such as seaweeds – because mass production of energy is believed to mainly concentrating on these typically unicellular algae due to their less complex structure, fast growth rate and high oil content (for some species).

Hydrogen production which occurs in some types of unicellular green algae (i.e. Chlamydomonas reinhardtii) is not covered in this paper due to the special systems conditions (decrease of photosynthetic activity through sulphur deprivation) which are necessary to stimulate hydrogen production by microalgae. For hydrogen production by direct photolysis in microalgae photo-conversion efficiencies of up to 2% have been reported for lab experiments [5].

2 OPPORTUNITIES

Microalgae are very efficient in converting solar energy into chemical energy: up to 5% photo-conversion efficiency (PCE) can be achieved [6]. The yields reported or claimed for microalgae outperform traditional energy crops (Table 1). However, they can differ greatly depending on the species, the production system and conditions and the source of the data (lab, pilot or commercial unit).

Table I: Estimated yields of microalgae [7]

Land plants/ Microalgae production systems	Annual productivities (Mg DM/ha)
C3 land plants	8–10
C4 land plants	10-30
Open raceway ponds (paddle wheels)	20
Tubular reactor (mixing via air and CO_2)	60
Tubular reactor (dilution of light)	80
Flat panels (inten. mixing, short light-dark periods)	100

In commercially operated open ponds yields cover a vast range from 3.5 to 10-30 Mg dry weight ha^{-1} $year^{-1}$ [8, 9] with highest productivities achieved under tropical or subtropical conditions. In tubular or flat plate reactor systems much higher yields can be obtained than in open ponds (Table 1). In photo-bioreactors up to 150 Mg ha^{-1} $year^{-1}$ have already been reported for a limited duration [10]. However, such extremely high yields can only be obtained in photo-bioreactors which are operated indoors with intensive mixing and artificial lightening and provided that all production conditions (e.g. temperature, CO_2 levels, sunlight and nutrients) are optimized. Until today such high yields have not been reached as a time-average value for larger areas. This may be one reason why until today only a few hundred Mg of microalgae biomass per year is produced in closed bioreactors (e.g. Haematococcus in Japan and Israel, Chlorella in Germany).

Many microalgae have the ability to produce substantial amounts of lipids, hydrocarbons and other complex oils (between 15% and up to 80% of dry weight and of triacylglycerols (20-50% of dry cell weight) as a storage lipid. Their annual oil yield can be significantly higher compared to traditional oil crops (Table 2).

Table II: Oil productivities of crops and algae [7, 11]

Biomass Sources	Oil Productivities (L/ha/year)
Sunflower	390
Soybeans	440
Rapeseed	1,300
Jatropha	1,900
Oil palm	6,000
Microalgae (PCE 3 %; 40 % lipids; NL)	18,000

Microalgae produce storage lipids only under photo-oxidative stress or other adverse environmental conditions. Nitrogen deprivation, high light intensity, low temperature, and high salt or iron concentration can stimulate lipid formation. Since thermodynamic limits have to be respected a PCE of more than 5% is not likely to be achieved, because growth rates of oil producing microalgae will be smaller during production phase than under growth phase. For the most microalgae strains under cultivation no efficiency data are available, considering real day/night cycles and optimized limitation strategies for high oil productivities. In addition, to date no scalable, commercially viable system to produce lipid-rich microalgae for biofuel production exists.

Apart from higher area-specific biomass and oil yields, microalgae offer some more advantages compared to energy crops:

- microalgae cultivation systems have no requirements regarding soil quality and a low water demand;
- continuous biomass production (harvest daily) with less dependency from weather conditions is possible;
- algae can be cultivated in brackish or sea water;
- algal cultivation can limit negative effects of biomass production to humans and nature;
- nutrients requirement of algae could be covered by utilising waste streams such as CO2 from fossil-fuel fired power plants and nitrogen and phosphate from wastewater; and
- a tailored-made co-production of food, feed and high-value chemicals is feasible.

Hence, microalgae systems could contribute to a sustainable bioenergy production. However different biotechnical, environmental and economic challenges have to be overcome before energy products from microalgae can enter the market.

3 BIOTECHNICAL CHALLENGES

Only relatively small and mainly simple microalgae systems are in currently commercial operation [12]. For mass production of energy products the techniques and processes applied have to be further developed and up-scaled to become competitive with other techniques to generate energy. The biotechnical challenges addressed below include cultivation, harvesting and genetic engineering of microalgae as well as the conversion of algal biomass into methane by anaerobic digestion.

3.1 Large-scale cultivation

The majority of commercial microalgae production occurs in relatively unsophisticated, low-productive artificial open ponds, mostly circular or ‘raceway’ ponds. These are man-made structures (made from plastic or concrete) with 10-20 cm water that are subjected to circulation and mixing [13]. To suppress competing algae and zooplankton (‘grazers’), the culture of specific microalgae is currently restricted to open ponds with extreme conditions such as very high salinity or high pH. Sustained open pond production has been successful only for a limited number of microalgae such as Spirulina, Chlorella and Dunaliella. Open ponds can be built and operated relative economically and hence offer many advantages as long as the species for cultivation can be maintained.

Despite the success of open systems, future advances in microalgae cultivation might require closed systems as not all algal species on interest do grow in highly selective environments. The concept of closed systems has been around for a long time. However, their high costs have largely precluded their commercial application until recently. In the meantime several major advances in the design and operation of closed photo-bioreactors have been achieved and several systems are likely to be commercial realities in the near future. The basic designs of photo-bioreactor are flat plates, tubular reactors or bags made of plastics, glass or transparent materials. The cultures are circulated either by a pump or an air lift system.

Light is the source of energy for algal growth, but too high light intensity may result in photo-inhibition or overheating. That's why the physics of light distribution and the efficient utilization of light inside the photo-bioreactor is one of the major biotechnical challenges in bioreactor design. Photo-bioreactors allow good control not only over illumination, but also over temperature and other production parameters. Besides, contamination is less likely, so different and more productive species can be produced. The further development of photo-bioreactors for large-scale energy production must consider

- seasonal and diurnal changes in irradiance,
- the biomass growth kinetics, photo-inhibition and flashing-light effect,
- mass transfer of carbon dioxide and the photosynthetically generated oxygen,
- fluid mechanics, and
- peculiarities of the species being cultured (e.g., shear stress tolerance).

Equipped with internal illumination arrangements bioreactors can reach high cell densities of up to 20 g/L compared to less than 1 g/L in open ponds which facilitate harvesting and improve the efficiency of the total system. However, high sophisticated photo-bioreactors may be difficult to scale-up and lead to a high demand for auxiliary energy, and high investment and operation costs.

3.2 Efficient recovery and extraction

Microalgae cultures are usually very dilute suspensions with concentrations between less than 1 g/L (ponds) and 3-15 g/L (tubular or flat panel reactors) [7]. Several techniques for harvesting microalgae are available. These include centrifugation, flocculation and sedimentation, and filtration. In microalgae production for high-value products harvesting is generally done by centrifugation, flocculation with alum, ferric chloride or chitosin and hydrophobic absorbants or adsorbants [14].

However, the costs and energy demands for harvesting algal biomass by these methods are high. For example, the cost of dewatering microalgae for lipid extraction can make up 20–30% of the total cost for lipid concentrates. Thus, present harvesting techniques are not applicable for large-scale and low-cost harvesting to produce low-value energy products.

Different approaches exist for a further development of harvesting techniques. A technique with a low-energy demand is settling of algae by induced flocculation (Figure 2). Interrupting the CO_2 supply to the algal system can cause algae to flocculate on its own (auto-flocculation). However, flocculation of algal biomass is still poorly understood and the optimal conditions of the microalgae and the culture medium needed for effective flocculation are often unpredictable, which makes it difficult to control this harvesting process.

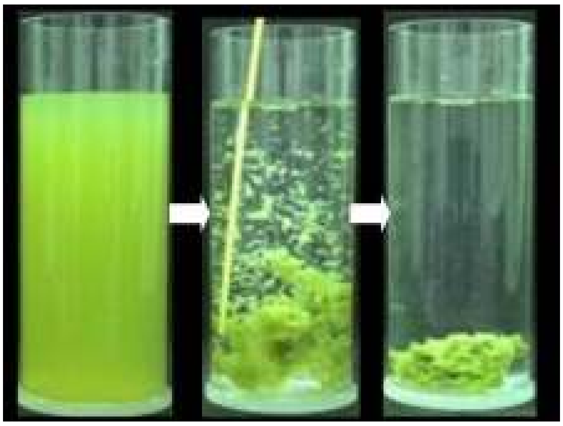

Figure 2: Flocculation of algae

Extracting lipids from microalgae is another biotechnical challenge due to the sturdy cell wall making the oil hard to get at. Typically, the oil is expelled from the dried algae by using a press to physically squeeze it out. The leftover mashed-up pulp is then treated with a solvent to remove any remaining oil. While the combination removes about 95 % of the oil, it is energy intensive.

Alternatively, the algae pulp can be treated with supercritical fluids that can remove nearly all the oil, but the process requires special machinery, adding to the expense. Another extraction technique under investigation is the combination of ultrasound and electromagnetic pulse to break the algal cell walls. Then the algae solution is force-fed carbon dioxide, which lowers its pH, separating the biomass from the oil.

In recent times, a method was described to harvest β-carotene from microalgae (Dunaliella salina) grown in a two-phase bioreactor and to re-use the algae for continuous production [15]. This result raises the question of whether this 'milking technique' could also be used in the mass production of secondary metabolites. Understanding the mechanism of the 'milking process' and its relationship to the product formation pathway should reveal whether other products (e.g. lipids) can be milked from various species of microalgae.

3.3 Genetic engineering of microalgae

Among the around 10,000 algae species that are believed to exist, only a few thousand strains are kept in collections, a few hundred are investigated for chemical content and just a handful microalgae (e.g. Chlorella, Dunaliella salina, Haematococcus pluvialis) are cultivated in industrial quantities [4]. Although some of these algae have been commercially cultivated for a long period of time, metabolic engineering of microalgae now seems necessary in order to enhance productivity, achieve their full processing capabilities and to optimize them for cultivation and harvesting (Figure 3).

Although the use of transgenic microalgae for commercial applications has not yet been reported, several examples of engineered microalgae for biotechnological applications show significant promise. The development of a number of transgenic algal strains boasting recombinant protein expression, engineered photosynthesis, and enhanced metabolism encourage the prospects of engineered microalgae [16]. The manipulation of microalgae lipid production by genetic engineering was one of the first reported approaches for the production of bio-diesel by transgenic diatoms. Another example is the modification of photoautotrophic diatom to live in the dark with glucose as the only carbon source.

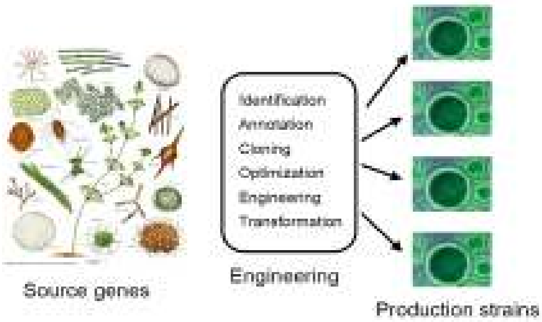

Figure 3: Genetic engineering of microalgae

Large-scale cultivation of genetically modified strains of algae compounds the risks of escape and contamination of the surrounding environment and of crossing with native strains. Moreover, modified microalgae could be transported in the air over long distances, and survive a variety of harsh conditions in a dormant stage. Thus, cultivation of genetically modified algae can have unintended consequences to public health and the environment and could constrict public confidence in microalgae cultivation systems. These concerns have to be integrated in the design of large-scale production systems working with modified microalgae.

3.4 Conversion of algal biomass into energy

There are different thermo-chemical and biochemical processes and techniques to convert algal biomass into useful energy products (e.g. fuel, electricity). Each of them has its own technical challenges with respect to the specific processes used to produce algal-based biofuels. Here only the biotechnical challenges of the conversion processes of the production of methane in biogas plants will be addressed because anaerobic digestion is regarded as the most direct way of energetic usage of microalgae.

For the anaerobic digestion in biogas plants after microalgae cell concentration via filtration or centrifugation, no further processing is necessary because biogas plants can deal with the relatively high water content. Another advantage considers logistics, as microalgae cultivation and biogas production are basically decentral technologies. CO_2 and minerals could be fed back to the algae production stage quite efficiently. However, process engineering designs have yet to be developed. Anaerobic digestion is also an energetic option for the residual algal biomass after extraction of oil for biodiesel production. However, there are also technical hurdles to be overcome.

The three main bottlenecks to digest microalgae are [17]:

- low biodegradability of microalgae depending on both the biochemical composition and the nature of the cell wall;
- high cellular protein content results in ammonia release which can lead to potential toxicity;
- presence of sodium for marine species can also affect the digester performance.

Further research is needed to analyse the fermentability of algae as mono-substrate and co-substrate and to clarify maximum gas yield, the influence of the salt content and possible co-substrates and pre-treatments. Pre-treatment, co-digestion, or control of gross composition are strategies that can significantly and efficiently increase the conversion yield of the algal organic matter into methane. When the cell lipid content does not exceed 40%, anaerobic digestion of the whole biomass appears to be the optimal strategy on an energy balance basis, for the energetic recovery of cell biomass [17].

4 ECOLOGICAL CHALLENGES

The cultivation of microalgae for energy generation can contribute to sustainable energy supply. To do so, the microalgae production systems need to be further developed to design systems with a favourable energy and nutrients balance. A major advantage of microalgae is their ability to capture additional environmental benefits except from substituting fossil fuels. However, to realize these benefits (CO_2-recycling and wastewater treatment) some hurdles need to be overcome. These environmental issues of microalgae production are addressed below.

4.1 Energy balance

Growing and processing microalgae consumes energy, both in infrastructure and operation. Depending on the cultivation system and the process of harvesting and processing, and on the yield, the energetic inputs of microalgae production can exceed the energetic output. In closed simple-build reactors more than 3 W/m^2 electrical energy are used for operating the cultivation. This comes close to the amount actually harvested at the end [18].

However, it has to be taken into account, that in commercial algae cultivation today, a positive energy-balance was not targeted due to the high-prices achieved for the products. Ongoing research in the reactor design is promising and will lead to cheaper and more energy-effective designs [19].

4.2 Capturing and recycling of CO_2

For microalgae, water, nutrients and carbon dioxide (CO_2) are vital to growth. The atmospheric CO_2 concentration limits the growth of microalgae. Thus, a cheap source of CO_2 to fuel their photosynthesis process is needed. Industrial and power plants fired with fossil fuels could be such a source (Figure 4) adding extra revenues from greenhouse gas abatement to microalgae production [20, 21, 22].

The first conceptual development of this idea (in 1960) described a large-scale system with dozens of large (40 hectares) high rate ponds, and with the biomass harvested by a simple flocculation-settling step, and the concentrated algal sludge anaerobically digested to produce biogas [14]. The biogas would be used to generate electricity and the flue gas CO_2, along with the nutrients in the digester effluent, used to grow more algae

(Figure 4). Make-up water and nutrients (C, N, P etc.) would be provided from wastewater. An efficiency of algal CO_2 capture in open ponds of 30 % has been claimed.

In Japan a large governmental-sponsored program, involving many private companies, on microalgae bio-fixation of CO_2 was carried out during the 1990's. This program focused on mainly closed photo-bioreactors, including optical fibre systems, for fixation of CO_2 and co-production of high value products. Currently in the U.S. similar concepts are being developed, and in Germany different power producer (e.g. RWE, E.ON) have recently launched projects to investigate the ability of closed algae bioreactors to convert CO_2 from flue gas into algae biomass.

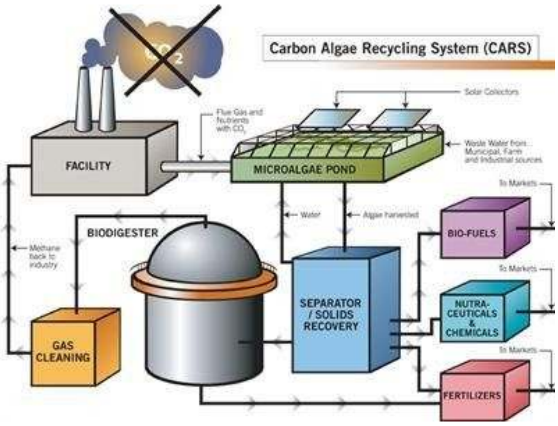

Figure 4: Carbon Algae Recycling System

If the purpose of algae cultivation is to sequester the industrial CO_2 outputs of fossil-fuelled power plants, it has to be taken into account, that during the night (and in poor weather, e.g. cloudy days) the algae slow down their reproduction rate and thus take up less CO_2. This would require the installation of gas storage facilities to cope with the influx of CO_2 during the night.

Whether the application of CO_2 capture by microalgae will be important in the future depends on

- solution to overcome the problems of CO2 capture by algae,
- the emission requirements for power and industrial plants, and
- risk perception and acceptance for CCS.

Before commercial-scale deployment of microalgae systems becomes feasible the challenge of limited availability of land for large-scale CO_2-capturing from industrial or power plants by microalgae have to be overcome by sophisticated area-efficient techniques to recycle CO_2 by microalgae.

4.3 Nutrients requirement

Growth medium for algae must provide the inorganic elements that constitute the algal cell. Essential elements include nitrogen (N), phosphorus (P), iron and in some cases silicon. Microalgae have high nutrients requirements and are exhibiting this in high contents of N and P, about 10 % and 1 % respectively on a dry weight basis, several-fold higher than of higher plants. Minimal nutritional requirements can be estimated using the approximate molecular formula of the microalgal biomass, that is $CO_{0.48}H_{1.83}N_{0.11}P_{0.01}$ [23]. Based on this calculation method the nitrogen requirements vary from 8 to 16 Mg N ha^{-1} $year^{-1}$. Some nutrients must be supplied in significant excess, because only parts of them are bioavailabe (e.g. P complex with metal ions).

Thus, microalgae cultivation will involve huge quantities of N and P for which environmental and economic impact may not be sustainable. Therefore, strategies to reduce the demand of fertilizers are required. Different approaches are feasible such as:

- selecting algal strains which contain less proteins;
- recycling nitrogen and phosphorus contained in algal biomass, products and waste, e.g. by extraction of nutrients via anaerobic digestion;
- application of waste nutrients (in wastewater);
- genetic engineering of nitrogen fixing microalgae.

Microalgae ponds have been utilised for several decades for the treatment of municipal sewage and other wastewaters, with the microalgae mainly providing dissolved oxygen for bacterial composition of the organic wastes. The major limitations in recycling nutrients from wastewater are the relatively low loadings that can be applied per unit area-time, limited nitrogen and phosphorus removal, increasing land requirements, and the high cost of removing the algal cells from the ponds effluents, using chemical flocculation or other means. In high-productive closed reactors, the wastewater must first be processed by bacteria, through anaerobic digestion to avoid contamination or destruction of the desired algae in the reactor.

Recycling the nutrients via anaerobic digestion of algal wastes could also be an answer to the nutrients challenge of microalgae production, since this process can mineralise algal waste containing organic nitrogen and phosphorus, resulting in a flux of ammonium and phosphate that can then be used for the microalgae. The residues from anaerobic digestion are liquid and nutrient-rich, and are nearly suitable for algae growth, but first need to be cleaned and sterilized. However, not all of the nitrogen can be recycled because the protein fraction of microalgae results in ammonia release [17].

Another concept to minimise the demand of nitrogen fertiliser might be to engineer photosynthetic algae in a way that they are capable to fix nitrogen.

4.4 Availability and suitability of land

Microalgae produce much higher yields than traditional energy crops and thus need much less land. Besides, microalgae production can take place on marginal land or in desert areas. Nevertheless, it is unclear how much land is available and suitable to produce high yields and utilise waste CO_2 and nutrients. Besides, the acceptance of large-scale microalgae production in rural areas should be investigated due to the significant changes in land use associated with algae production (Figure 5).

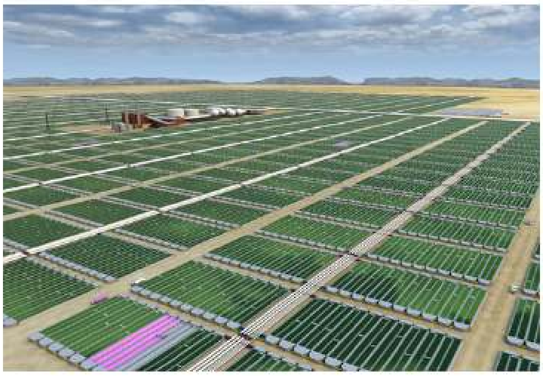

Figure 5: Vision of large-scale algae production

Most of the earth's surface is covered by water. Thus, one way to face the land requirements for algae cultivation might be to produce on water surfaces or in water.

5 ECONOMIC CHALLENGES

The development of microalgae for mass energy production is in its infancy. Because of that it seems critical to base cost assumptions on state-of-the-art techniques used for small-scale production of high-value products. Moreover, calculations on the economics of microalgae systems are highly sensitive to the assumptions made about costs and revenues of microalgae production systems. This becomes obvious looking at the results of cost assessment studies for microalgae. The production of algal biomass is estimated to cost 4-10 €/kg biomass [7]. The total costs for concentrating microalgae from 0.3 g/L to 100 g/L (10% dry matter) can be reduced from around 2.70 €/kg (for centrifugation) to about 0.7 €/kg when the algae are pre-concentrated to 5% dry matter by flocculation combined with flotation or sedimentation prior to further concentration by centrifugation or filtration.

The cost assessments for producing oil from microalgae vary in a vast range between 1.20-1.50 and 3 €/L [16, 24]. Compared to the production of rapeseed oil (0.5 €/L) and 2nd generation biofuels (1 €/L for large-scale plants), the costs for algal-based biofuels need to be decreased significantly to become competitive. Cost of producing microalgae biofuels can be reduced substantially by increasing cell concentrations and the content of lipids, and decrease the investment and operation costs for cultivation and harvesting.

Economics of microalgae production can also be improved by capturing additional revenues from

- co-production of food, feed and high-value products,
- GHG abatement,
- wastewater treatment, and
- net fertiliser value in case of nitrogen fixing algae.

6 CONCLUSION

The present attempts to develop large-scale microalgae production systems for energy generation stem from the perceived inadequacies in the potential of traditional biofuel feedstock for meeting future demands, the climate change and the CCS debate, and criticisms that biofuel agriculture as it is practiced today is not sustainable and environmentally harmful.

Microalgae have many advantages over traditional energy crops, such as the potential for high-yield biomass production on marginal land or in seawater. Current production of algal biomass is primarily confined to high-value products and not suitable for the production of commodity bioenergy products. However, microalgae production could become economically feasible in the future when biotechnical, environmental and economic hurdles will be surmounted.

The big challenge of microalgae systems is to produce algal biomass or algal-based fuels economically. A reduction of production costs is possible by using microalgae for environmental services such as CO_2-recycling and wastewater treatment. Another option to enhance the economic efficiency is the co-production of food, feed, and high-value products such as food supplements. Hence, endeavours should be undertaken to ensure that microalgae systems can capture these additional revenues.

Since microalgae production systems are still in their infancy, cost reduction due to progress in research and technology development is expected. Long-term R&D in biotechnology is needed to develop efficient algal mass cultivation, harvesting and extraction systems with high productivity, nutrients removal and a positive net energy balance. Above all harvesting and dewatering of microalgae cultures is a major bottleneck towards industrial-scale processing of microalgae for biofuel production. The challenge is to develop an efficient and versatile microalgae separation process workable for all microalgae strains, with a high dry biomass weight percentage and only moderate cost for investment and operation.

Whereas microalgae can produce various energy carriers (e.g. oil or hydrogen) and as algal biomass can be converted through several thermo-chemical and biochemical processes, technology assessment studies are needed to find out which strategy can contribute most to a sustainable supply of bioenergy. In addition, land availability for microalgae production systems should be assessed and suitable production sites identified.

The competencies necessary to strengthen the competitiveness of Europe in microalgae systems for energy production are currently rather scattered and should to be linked. Furthermore, a roadmap to strategically support the development of microalgae energy systems in Europe is needed.

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