MSc Program
Renewable Energy in Central and Eastern Europe

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In How Far Can Algae Based Bioenergy Contribute to Our Electric Power Supply?

A Master's Thesis submitted for the degree of "Master of Science"

supervised by
Dr. Mario Ortner

Dipl.-Ing. (FH) Franz Mühlbacher

9025385

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Affidavit

I, **Franz Mühlbacher**, hereby declare

1. that I am the sole author of the present Master Thesis, "**In How Far Can Algae Based Bioenergy Contribute to Our Electric Power Supply?**", 115 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master Thesis as an examination paper in any form in Austria or abroad.

Vienna, Oct. 20, 2010 Dipl.-Ing. (FH) Franz Mühlbacher

Date Signature

Abstract

The world's demand for energy increases year by year neglecting the threat of vanishing fossil resources. At the same time electricity gains importance concerning its share within the final energy consumption. The sustainable supply with (electric) energy is crucial, from first world to third world countries. Around the world, bioenergy related research shows interest in algae as a promising future energy carrier which once may replace fossil resources.

These developments pose the question "**In How Far Can Algae Based Bioenergy Contribute to Our Electric Power Supply?**"

This Master Thesis aims to answer the question by diving into the details of algae biomass.

Introductorily, a chapter about biology describes algae as a summary of a vast variety of individual organisms using photosynthesis to store solar energy as biomass. The description of how biomass can be transformed into useful energy is followed by the definition of achievable biomass yields. Biogas is described as an interesting intermediate product in the process of generating electricity out of algae biomass. An economic spotlight is put on the feasibility of switching the conventional maize feedstock of an existing CHP plant to algae biomass.

It gets obvious that the potentials of algae as a future energy source in general and as a considerable electricity producer in particular are impressing. However, it can also be seen that algae technology stands at the beginning of an economic learning curve.

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Abbreviations and Symbols

Units of energy

W h, J, Toe Watt hour, Joule, ton of oil equivalent

Energy Conversions

1	J	=	1	W s			
3.6	kJ	=	1	W h			
3.6	PJ	=	**1**	**TW h**	=	0.086	Mtoe
1	**PJ**	=	0.278	TW h	=	0.024	Mtoe
41.868	PJ	=	11.63	TW h	=	**1**	**Mtoe**

Magnitudes of Energy

1 EJ = 10^3 PJ = 10^6 TJ = 10^9 GJ = 10^{12} MJ = 10^{15} kJ = 10^{18} J

SI-Prefixes

exa	peta	tera	giga	mega	kilo
E...10^{18}	P...10^{15}	T...10^{12}	G...10^9	M...10^6	k...10^3
a...10^{-18}	f...10^{-15}	p...10^{-12}	n...10^{-9}	µ...10^{-6}	m...10^{-3}
atto	femto	pico	nano	micro	milli

Units of area

1 ha = 10,000 m^2

Abbreviation	Definition
a	Year
ADP	Adenosine diphosphate
ATP	Adenosine triphosphate
ASP	Aquatic Species Program by NREL
B_{12}	Vitamin B_{12}
c	Speed of light
C	Carbon
CH_4	Methane
$C_6H_{12}O_6$	Sugar
CHP	Combined Heat and Power
Cl	Chlorine
CNG	Compressed natural gas
CO_2	Carbon dioxide
CPP	Coal fired power plant
CV	Calorific value
DNA	Deoxyribonucleic acid – holds genetic information

DO	Dissolved oxygen
DOE	U.S. Department of Energy
e^-	Electron
E	Energy
eV	Electron volt (unit of energy)
FME	Fatty acid methyl ester
h	Planck's constant
H, H_2	Hydrogen
HHV, Ho	Higher heating value
H_2O	Water
IEA	International Energy Agency
λ	Wavelength (for instance, of light)
L	Litre
LHC	Light harvesting complex
LHV, Hu	Lower heating value
m	Meter; mass
mol	Mole
N_A	Avogadro's number
Na_2SiO_3	Silicate
NADP	Nicotinamide adenine dinucleotide phosphate
NADPH	Nicotinamide adenine dinucleotide phosphate-oxidase
NH_3	Ammoniac
NH_4Cl	Ammonium chloride
NO_x	Nitrogen oxide
NREL	National Renewable Energy Laboratories, USA
O, O_2	Oxygen
OP	Open pond system
oTS	Organic dry matter
P	Phosphorus
P, P_{el}, P_{th}, P_{loss}	Power, electric power, thermal power, power loss
pH	pH value
PAR	Photosynthetic active radiation
PBR	Photobioreactor
PE	Photosynthetic efficiency
PSI, PSII	Photo system 1, photo system 2
PVGIS	Photovoltaik geographical information system
RME	Raps methyl ester
s	Second
S	Sulphur
Si	Silicon
UV	Ultra violet (light)
v	Frequency
WACC	Weighted average cost of capital

1 Introduction

In societies all over the world there is the more or less developed need for energy services, such as lightening, space heating and cooking, mobility and transport, information technology and so forth (Haas, 2008).

Energy services are generated from *primary energy sources*, for instance, wood, solar energy, crude oil, coal or natural gas. Primary energy is, in general, energy that has not been technically converted. The primary sources are converted into so called *secondary energy*, e.g. electricity, pellets, biodiesel or gasoline. Secondary energy is has be delivered to the final customer in suitable portions, for instance, pellets at the storage of the heating system. Therefore, it is named *final energy*. At the consumer it is subsequently transformed into *useful energy*, for instance, heat, light and mechanical work. Finally, the *energy services* are driven by the useful energy and deliver, for example, warm and bright rooms, mobility and any other comfort people desire. The whole chain from primary energy to energy services is called *energy system*; each conversion is accompanied by *transformation losses* (Hofbauer, 2009).

Figure 1 gives an overview of the development concerning the shares of total final consumption from 1973 to 2007. The data is taken from the IEA. In 2007, *electric energy* covered about 17.1% of the global final energy consumption and is the most increasing form of final energy. Compared to a value of 9.4% in 1973 it nearly doubled. The fraction of oil decreased from 48.1% to 42.6% but still holds the largest percentage; coal also decreased from 13.2% to 8.8%. Natural gas is stable at approximately 15%. From 1973 to 2007 the total final energy consumption itself nearly doubled, increasing from 196 EJ (= 4,675 Mtoe) to 347 EJ (= 8,286 Mtoe) (IEA, 2009).

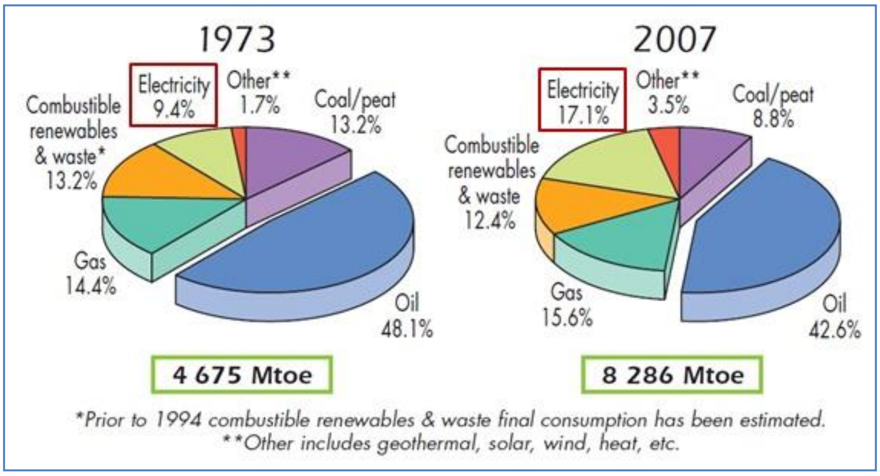

Figure 1: Fuel shares of total final consumption, 1973 and 2007
(IEA, 2009)

Austria's consumption of electric energy in 2008 was approximately 211 PJ which is about 19.4% of the total final energy consumption of about 1 EJ (Statistik Austria, 2009). Following the global trends it can also be observed that the share of electricity is increasing.

Due to the fast growing fraction of electric energy this paper will concentrate on the *generation of electric energy* using a renewable and sustainable primary energy source in general and having a focus on algae as biomass source in the particular case.

1.1 Motivation

Picture 1: Sea lettuce – Ulva lactuca
(Source: www.pt-lobos.com/algae.html)

My motivation to write this work is driven by the fascinating possibilities renewable energy sources offer. First and foremost, biomass is very interesting for me because it represents stored solar energy and because I am sure that our renewable future will be mainly solar powered. After a rather short period of about 150 years with the predominance of fossil energy sources especially in the higher developed countries solar energy and its derived resources such as biomass and also wind energy will re-establish their importance with respect to covering people's demand for energy.

Reading about peak oil and vanishing fossil resources does not panic me. In fact, it gives me hope that renewable sources will get back their importance they almost always had.

Algae are one of the eldest life-forms on earth. They have developed a nearly endless number of species, all of them using solar resources to produce biomass and oxygen which is the base for all known life on earth. Compared to technical innovations such as solar panels algae do not have to be developed any further to convert solar energy into useful energy. The only thing that has to be done is to select the most efficient species and strains of algae to produce organic matter under certain conditions which then can be transformed into fuels and electric energy, respectively.

Algae offer the possibility to utilise solar energy combined with genetic knowledge that has been developed over millions of years: Since ancient times, algae have been producing the main part of the oxygen within the atmosphere; in a renewable future they may deliver even remarkable shares of needed energy.

1.2 The Core Question

The core question of this paper is formulated as an open question. This question is often asked when algae biomass is considered.

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This question subsumes a list of detailed questions concerning algae as an energy source.

- How do algae differ from other plants?
- How can the flows of biomass generating components (light, water, carbon dioxide) be characterised?
- How efficient can algae transform solar energy into biomass?
- What are the aspects for the selection of utilised algae strains?
- How can algae be utilised for energy purposes?
- How does the logistic path of growing and harvesting of algae biomass look like?
- How can the total efficiency of an algae biogas powered electricity production be estimated?
- How big is the potential for growing algae for energy purposes in Central European regions and especially in Austria?

- What are the competing applications of algae besides energy production?
- How can the roadmap for utilising algae as an energy source look like?

1.3 Citation of Main Literature

The main literature which is cited is of international origin and is allocated around algae's physiology and bio factors on the one hand and around optimised growing, harvesting and biomass conversion methods for energy purposes on the other hand. The cited literature also provides background information in the fields of thermodynamics, biomass utilisation, physics and biology. Beside books, conference proceedings and web resources have been used; the list of literature is completed by scripts provided by TU Vienna in the course of the MSc Program "Renewable Energy in Central & Eastern Europe.

1.4 Structure of work

The paper is structured in the following main areas:

- The core question and derived questions
- Collection of data
    - Theoretic data
        - Biology and taxonomy (classes and species)
        - Growing and harvesting algae
        - Biomass and conversion paths, Generation of electricity
    - Mass flow and energy balance
        - Capacities and theoretic potential
        - Biogas yields and Electricity production
    - Practical applications
        - Algae as an alternative fuel for existing biogas CHP plants
        - Municipal wastewater treatment in combination with algae
    - Economic aspects
        - Upgrading existing CHP plants
        - Cost comparison: conventional feedstock vs. algae feedstock
- Evaluation of data
    - Answer to the core question and derived questions
- Conclusion

2 Approach and Methodology

In how far can algae based bioenergy contribute to our electric power supply?
In order to find an answer to the core question this paper takes a look at algae biomass from various angles and collects faceted snapshots concerning algae.
Firstly, the biologic factors are taken into consideration. Microalgae are defined as the object of interest, namely the primary energy source throughout the paper. Photosynthesis is described in detail in order to define out the photosynthetic efficiency of algae. It is explained how algae may be converted into secondary energy and which intermediate products and conversions can be applied to realise the desired conversion.
Secondly, mass flow and energy balance are studied. Production capacities of algae are compared to the capacities of maize. It is calculated how much biomass can be generated depending on the intensity of the impelling sunlight. The chapter also estimates how much biogas can be yielded and how much electricity can be produced using biogas as intermediate product.
Thirdly, practical examples of possible algae utilisation are outlined. On the one hand it can be seen how algae may replace conventional feedstock at an existing CHP plant with an onsite biogas generation. On the other hand it is described how a municipal wastewater treatment system could be modified by the utilisation of algae.
Finally, the economic aspects concerning the feedstock replacement in the first example are depicted.
The following chapter gives answers to the main questions which have been defined at the beginning of the paper by combining the details as depicted in the data collection snapshots.
A conclusion finalises this paper.

The annexes deliver additional information on algae such as web sites covering algae as energy source, algae research projects, sources for algae culture recipes, design issues for building algae pond systems, the legal situation concerning algae related projects in Lower Austria and pictures of some algae species which are mentioned in this paper.

3 Algae as a Renewable Energy Source – Data Collection

The data collection builds up a factual base concerning algal biomass from different points of view: theoretic data is combined with practical data from existing biomass plants and possible use cases. It is concluded by an economic evaluation of the potentials of algae as an alternative biomass fuel for the future.

3.1 Theoretical Fundamentals

This section provides a collection of data concerning algae as living organisms that exist in an enormous number of species and strains. It describes the processes that transform solar energy into biomass by depicting the photosynthetic process, growing and harvesting algae and the value of algal biomass as an energy source. It further describes the products and fuels, respectively, that can be derived from the biomass.

3.1.1 Preface – Biomass as a Renewable Energy Source

All forms of energy that can be utilised on earth have their origin in one of three main primary energy sources. These are *tidal energy*, *geothermal energy* and *solar energy* which is by far the most important source. The Sun delivers an amount of energy which is approximately 10,000 times as high as the world energy demand. The global solar irradiation on a sunny day with clear sky averages at about 1,000 W/m² on the ground (Fechner, 2008), (Kaltschmitt, M. et al. [Hrsg.], 2009).

As biomass is generated by plants using solar energy via the vehicle of photosynthetic processes it is stored solar energy. The storage aspect makes the most significant difference compared to forms of derived solar energy such as wind energy or solar thermal applications.

3.1.2 Biology

Algae are expected to have a promising role for future energy production. These prospects are based on their biological and biochemical attributes which will be explained within the following chapters. In general, algae play very important roles in the global ecosystem. On the one hand they build the lower end of the food chain in any bodies of water defining the basement for all forms of aquatic life (i.e. in oceans, seas and lakes). On the other hand algae's photosynthetic activities produce around fifty percent of the oxygen within our atmosphere while consuming corresponding amounts of the greenhouse gas CO_2. Compared to plants algae have a significant higher efficiency concerning the ratio of generated oxygen per ton of biomass.

3.1.2.1 Definition of Micro Algae and Macro Algae

"Algae" as a biological term does not have a defined taxonomic meaning. It can be defined as a polyphyletic[1], non contiguous and artificial collection of organisms that produce O_2 based on photosynthesis. According to this definition all plants could be seen as an algal division as all plants show some similarities with respect to biochemical processes. There are also morphologic analogies between some algae and plants. Nevertheless, plants show much more differences than similarities when compared to algae. Plants have a high differentiation between roots, stems and leaves; they build vascular networks. The reproductive cells of plants are covered by sterile cells; plants have a digenetic lifecycle, alternating between haploid[2] gametophyte[3] and diploid[4] sporophyte[5]. Plants show a multicellular diploid embryo stage which is dependent on the parental gematophyte.

In contrast, algae do not have any of these characteristics. They do not have roots, stems and leaves; algae do not build up differentiated vascular networks; in addition, algae do not build embryos. Reproduction is realised by cell structures which are potentially fertile. These structures are not covered by sterile cells. Algae can be found in a variety of formations, from single cells in microscopic structures to loosely coupled multicellular structures and colonies forming different shapes and blades. Overall it can be stated that algae are a separate group of organisms and there are almost no intersections with plants (Barsanti, et al., 2006).

[1]Polyphyletic: the term derives from Greek *poly*: numerous and *phyle*: stem. A polyphyletic collection of organisms summarises species that do not have a common origin but show similarities with respect to specific characteristics (Barsanti, et al., 2006).
[2] Haploid, derived from Greek *haplous:* single. In this context it defines a gamete having only the half of the complete set of chromosomes in somatic cells. (Biology-Online.org, 2007)
[3] A gametophyte is a plant or a phase of a plant's life cycle that bears gametes. (Biology-Online.org, 2007)
[4] Diploid: A cell or an organism consisting of two sets of chromosomes; normally one set from the mother and another set of the father. (Biology-Online.org, 2007)
[5] A sporophyte is a spore producing plant generation: It is the dominant generation in higher plants alternating with the gametophyte generation. (Biology-Online.org, 2007)

The term “algae” involves the two main groups of algal organisms: *macroalgae* and *microalgae*. Macroalgae are non-rooted aquatic plants also known as seaweed or kelp which can build giant structures of up to 60 meters in length. Microalgae, however, refer to a vast variety of photosynthetic and unicellular microorganisms ranging from 0.2 – 50 µm in size.

Macroalgae are grown in the sea, mainly for food related purposes and also because of their ability to produce gelling substances. Although there are some efforts to use macroalgae for energy purposes as well this paper refers to microalgae when addressing algae in general.

3.1.2.2 Species

Algae contain both eukaryote and prokaryote species. *Eukaryotes* are organisms such as animals, plants etc. having cells organised into membrane-bound cell compartments and structures called organelles and a nucleus in particular. The nucleus contains the sequenced DNA; DNA replication and protein synthesis are organised in a similar way among all these species. *Prokaryotes*, though, differ from eukaryotes mainly by the lack of true, membrane-bounded nucleus and other cell compartments such as mitochondria and chloroplasts. Prominent groups of prykaryotic organisms are *bacteria* and *archaea*[6] (Wageningen UR, 2010).

Examples for eukaryotic organisms are *protists* (i.e. all eukaryotes except animals, fungi and plants) including *diatoms* which are cited quite often in an algal context. In the literature the number of algal species is estimated to be as high as one to ten millions[7]; most of these species are microalgae (Barsanti, et al., 2006). Up to now only a small percentage, i.e. about 10%, of all existing species has been identified and studied, respectively. Therefore the playground concerning algal research and utilisation for special purposes is defined by a rather small number of single species. Depending on the desired output of the utilisation of algae the selection of suitable algae strains is essential. There are different approaches to organise the huge group of species. Due to the high movement driven by intensive research the classifications are redefined from time to time. Table 1 lists the main classes of

[6] Archaea (singular: archaeon) derives from Greek *archaion* (n.): ancient. Archaea are defined as unicellular microorganisms that are genetically distinct from bacteria and eukaryotes. They often live under extreme environmental conditions, for instance, in very hot (inhabited by thermophiles) or salty (inhabited by halophiles) environments (Biology-Online.org, 2007).

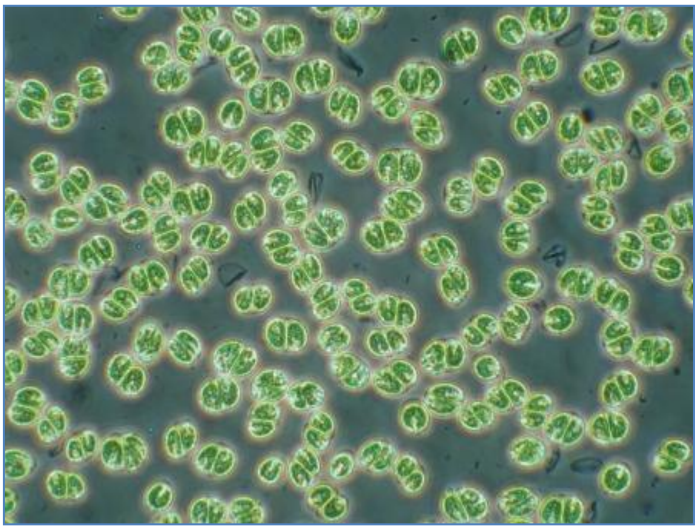
[7] The number of species of higher plants is estimated to be at a magnitude of approximately 250,000.

microalgae following a common organisation as found in literature. Chapter 3.1.4.1 provides a listing of algae with high oil content suitable for mass production.

Table 1: Classes of algae
(Wageningen UR, 2010), (Graham, et al., 2009)

Class	Examples
Bacillariophyceae (Diatoms)	Skeletonema, Thalassiosira, Phaeodactylum, Chaetoceros
Chlorophyceae (Green algae)	Chlorella, Dunaliella, Scenedesmus, Haematococcus, Nannochloris
Rhodophyceans (Red algae)	Porphyridium cruentum, Galdieria
Haptophyceae	Isochrysis, Pavlova
Prasinophyceae	*Tetraselmis*, Pyramimonas
Cryptophyceae	Chlamydomonas, Rhodomonas, Chroomonas
Xanthophyceae	Olistodiscus, Monodus
Eustigmatophyceae	Nannochloropsis
Dinophyceae	Crypthecodinium, Alexandrium, Gymnodinium, Chattonella, Karenia
Euglenophyceans	Euglena
Cyanophyceae (blue-green algae)	Spirulina, Synechococcus, Synechocystis, Cyanidium

All of the listed classes are eukaryotic, except the *Cyanophyceae* which are prokaryotic. Picture 2 shows a microscopic image of a species of the class Prasinophyceae.



Picture 2: Tetraselmis suecica (marine algae)
Magnification: 400 times (Wageningen UR, 2010)

3.1.2.3 Photosynthesis[8]

Photosynthesis is a light driven generation of organic matter and can be characterised a series of biochemical reactions converting solar radiation energy into biologically useable energy in the form of organic matter. It has established over the last three billions of years by the means of evolution. If these reactions release oxygen the process is called oxygenic, otherwise anoxygenic. Oxygenic photosynthesis introduces one of the thermodynamically most important chemical reactions in biology basically creating and enabling all forms of life on earth: the solar powered oxidation[9] of water in combination with the generation of free oxygen ($2H_2O \rightarrow 4H^+ + O_2 + 4e^-$). This chapter outlines the essential parts of the oxygenic type of photosynthesis in order to analyse the potentials of utilising biomass as a (future) energy source. In this paper photosynthesis stands for the oxygenic type of reactions. The data used in this chapter is taken from mainly two sources: the book *Algae – Anatomy, Biochemistry, and Biotechnology* by Laura Barsanti (Barsanti, et al., 2006) and the website *Photosynthesis and the Web: 2008* by Larry Orr (Arizona State University) and Govindjee (University of Illinois) (Orr, et al., 2008).

3.1.2.3.1 Basics

Photosynthetic reactions take place in photoautotroph organisms. This means that these organisms can generate food out of nonorganic matter such as water and carbon dioxide using light. The complex mechanisms can be clustered into light dependent reactions and light-independent reactions.

3.1.2.3.1.1 Light

The light emitted by the Sun is the driving force for organisms on earth. Light is defined as electromagnetic radiation that is emitted by nuclear fusion processes within the Sun. The radiation shows both wave and particle properties. With respect to the wave properties the sunlight can be classified as a broad band radiation that consists of rays with a spectrum of different wavelengths λ reaching from γ- and x-rays ($\lambda = 10^{-3} - 10\ nm$) to long radio waves ($\lambda = 10^{12}\ nm$). However, almost all (i.e. 99%) of the solar radiation is concentrated in a wavelength area of $300 - 4{,}000\ nm$ and is known as the broadband or total solar radiation.

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[8] Photosynthesis: the term derives from Greek *photos*: light and *synthesis*: formation.
[9] Oxidation is the complete, net removal of one or more electrons from a molecular entity; the oxidation number of any atom within any substrate is increased. (IUPAC.org, 2009).

It can be subdivided into

- ultra violet radiation (UV spectrum) $100 - 400\ nm$
- visible light $400 - 700\ nm$
- heat radiation (infrared spectrum) $700 - 4{,}000\ nm$

Figure 2 shows the regions of the electromagnetic spectrum (University of Washington - Department of Chemistry, 2006).

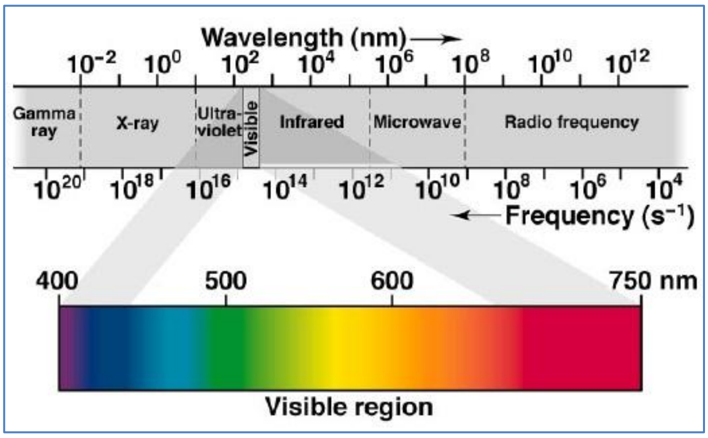

Figure 2: Regions of the electromagnetic spectrum
(University of Washington - Department of Chemistry, 2006)

In order to determine the energy which is contained within the radiation the particle properties of light are taken into consideration. In this case the radiation is thought to be a pulsed stream of so called photons or quanta causing the electromagnetic waves by oscillation. Each photon has a defined energy; it is defined by the following equation.

$$E_{photon} = h * v = h * \frac{c}{\lambda}$$

The first expression, namely h, is the Planck's constant ($h = 6.626 * 10^{-34}\ Js$); the second one, namely v, is the frequency of the photon. The frequency on the other hand is calculated by dividing the speed of light by the wavelength (i.e. c/λ where c is the speed of light; $c = 3 * 10^{8}\ m/s$). In the following the energy contents for typical wavelengths are calculated. For a photon with $\lambda = 300\ nm$ the energy amounts to

$$E_{P300} = 6.626 * 10^{-34}\ Js * \frac{3 * 10^{8}\ m/s}{300 * 10^{-9} m} = 6.626 * 10^{-34} * 10^{15}\ J = 6.626 * 10^{-19}\ J.$$

In analogy, the values for other λ-values can be calculated:

$$E_{P400} = 4.97 * 10^{-19}\ J;\ E_{P700} = 2.84 * 10^{-19}\ J;\ E_{P4000} = 0.497 * 10^{-19}\ J.$$

When photons are absorbed by molecules within the photoreceptors of the organism's light harvesting complex (LHC) the energy of the photon can be transformed into potential energy of excited electrons if they are knocked out of their atomic or molecular compound by the photon. Therefore the energy of a photon can also be expressed in terms of potential energy measured in electron volts eV ($eV = 1.6 * 10^{-19}\,J$). The corresponding values for different λ-values are:

$$E_{P300} = 4.14\,eV;\ E_{P400} = 3.11\,eV;\ E_{P700} = 1.78\,eV;\ E_{P4000} = 0.31\,eV.$$

For later calculations the energy per mole[10] of photons is important. It can be calculated by multiplying the energy of a photon by Avogadro's number ($N_A = 6.022 * 10^{23}$) which defines the number of entities in one mole (University of Washington - Department of Chemistry, 2006).

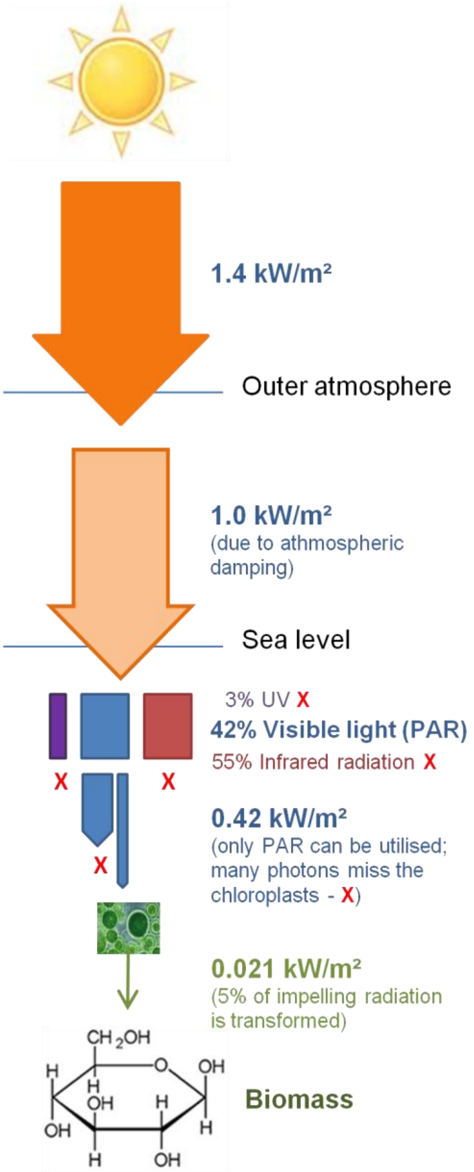

Figure 3: Light yield of an algal cell

$$E_{P300,mol} = 6.626 * 10^{-19}\,J * 6.022 * 10^{23}$$
$$= 399\,kJ$$
$$E_{P400,mol} = 299\,kJ$$
$$E_{P700,mol} = 171\,kJ$$
$$E_{P4000,mol} = 29.9\,kJ$$

The intensity of solar radiation arriving at the upper atmosphere is approximately $1.4\,kW/m^2$; the fractions of the different λ-values are 8% UV, 41% visible light and 51% infrared radiation. Caused by atmospheric resistances the intensity decreases until the radiation reaches the ground. On sunny and clear days it has an intensity of approx. $1.0\,kW/m^2$; also the fractions change: 3% UV, 42% visible light and 55% infrared radiation. On cloudy days the atmospheric attenuation can reach nearly 100%.

In aquatic areas the decrease is even stronger because up to the half (i.e. 3 – 50%) of the incoming light is reflected on the water surface. Within water the

[10] Mole: "SI base unit for the amount of substance (symbol: mol). The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon-12." (IUPAC.org, 2009)

different wavelength fractions are absorbed at different depths of the water. Ultra violet light as well as infrared radiation are absorbed within the first 2 meters; visible light can penetrate the water column for a longer distance. The red spectrum of visible light reaches 5 meters whereas the blue-green spectrum ($450 - 550\ nm$) reaches deeper areas (Barsanti, et al., 2006).

In terms of photosynthetic processes the visible part of the light is essential. Whereas the UV portion carries too much energy and can destroy the photoreceptors the power of the infrared radiation is too low to excite electrons within the light harvesting structures of photoautotroph organisms.

Therefore the visible spectrum of the light is called photosynthetic active radiation (*PAR*). Considering that the fraction of visible light is 42% of the total solar radiation this means that the intensity of PAR at sea level is about $0.42\ kW/m^2$. Under water the available energy per square meter is even lower. In addition, about 95% of the energy impelling to a single algae cell is lost by photons missing the receptors as well as by metabolic energy consumption and ineffectiveness of the biochemical processes. As a result only 5% of the light energy, which corresponds to $0.021\ kW/m^2$, is used to drive photosynthetic (i.e. biomass generating) processes. Figure 3 illustrates the light yield of algal cells in comparison to the solar irradiation at sea level. Only small portions of the available radiation energy are converted to biomass. Nevertheless, algae produce abundant amounts of biomass and are responsible for approximately half of the atmospheric oxygen (Barsanti, et al., 2006).

3.1.2.3.1.2 Light Dependent Reactions (Photo Systems PSI and PSII)

Photosynthesis basically transforms CO_2 into carbohydrates $[CH_2O]n$ by utilising light energy. The photosynthetic equation shows the main path of the reactions which can be described as complex redox[11] processes:

$$nCO_2 + nH_2O + light = (CH_2O)n + nO_2$$

This means that CO_2 which is maximally oxidised is transformed into strongly reduced carbohydrates. Carbohydrates may be re-oxidised later setting free the energy that has been invested and stored, respectively, during the transformation.

[11] An oxidation-reduction (redox) reaction consists of two half reactions: one in which a chemical participant is reduced (i.e. assimilates electrons) and one in which a chemical species is oxidized (i.e. electrons are taken away from the species). When the half-reaction is noted as reduction it is driven by the so called reduction potential; in case of an oxidation it is driven by the oxidation potential. The difference of the two potentials is the sign. That means that the redox potential is the reduction/oxidation potential of a compound measured under certain standard conditions (IUPAC.org, 2009).

With respect to the redox potential photosynthesis occurs in a redox potential area between $+0.82\,eV$ (redox potential of $H_2O \leftrightarrow O_2$) and $-0.42\,eV$ (redox potential of $CO_2 \leftrightarrow CH_2O$) (Barsanti, et al., 2006).

Photosynthesis mainly is carried out by two main groups of reactions. On the one hand there is the *light dependent group of reactions*; on the other hand it is the *light independent group of reactions*. The light depending part is located in the so called thylakoid membrane which is a dynamic structure within chloroplasts. This membrane is approximately $7\,nm$ thick and basically transforms the energy of photons into chemical energy. The reactants for the reactions are sunlight and water. Two separate units, namely *photo system I (PSI)* and *photo system II (PSII)* realise the energy transformation. Forming a super system they are surrounded by light harvesting complexes, so called antennas which collect the photons of the incoming sunlight by means of chlorophyll. The two photo systems have different historical roots and exist also as single systems within certain organisms. PSI is the elder one and is still used solely by sulphur bacteria. PSII is found as a separated system in purple bacteria. The first organisms using photosynthesis as the combination of both systems were cyanobacteria.

When working in teamed mode PSII precedes PSI. PSII consist of light harvesting chlorophylls (i.e. pigments P_{680}) which are excited at the maximum by light with a wavelength of $680\,nm$. The main function of PSII is the light driven oxidation of water, namely the separation of water into hydrogen and oxygen by the release of four electrons ($2\mathrm{H_2O} \rightarrow 4\mathrm{H^+} + \mathrm{O_2} + 4\mathrm{e^-}$) as mentioned earlier in this chapter. The hydrogen molecules as well as the released electrons are temporarily embedded into molecular storage structures; chemically this means that these structures are reduced.

Subsequently, the structures are handed over to PSI. PSI uses chlorophylls (i.e. pigments P_{700}) which are excited at the maximum by light with a wavelength of $700\,nm$. The main function of PSI in turn is the twofold. Firstly, it is the reduction of the coenzyme NADP+[12] to NADPH[13] by adding hydrogen that has been prepared and stored by PSII as described in the paragraph before; secondly, it is the generation of ATP[14] by putting together ADP[15] and inorganic phosphate (P_i).

[12] NADP stands for nicotinamide adenine dinucleotide phosphate.
[13] NADPH stands for nicotinamide adenine dinucleotide phosphate-oxidase.
[14] ATP stands for adenosine triphosphate.
[15] ADP stands for adenosine diphosphate.

In summa the light dependent reactions of photosynthesis can be explained as the transformation of light energy into a chemically useful energy by the means of teamed photo systems I and II via the dissociation of water:

$$4NADP^+ + 2H_2O + 4ADP + 4P_i \xrightarrow{8\,photons\ plus\ 4e^-} 4NADPH + 4ATP + O_2$$

Having a focus on the redox potentials the following can be stated. The redox potential of the oxidation of water ($0.82\ eV$) to reduction of $NADP^+$ ($-0.42\ eV$) sums up to a value of $1.24\ eV$. The system, however, uses a $680\ nm$ photon with a corresponding energy of $En_{P680} = 1.82\ eV$ and a $700\ nm$ photon with a correlative energy of $En_{P700} = 1.77\ eV$ (as calculated in 3.1.2.3.1.1) summing up to an energy of $En_{P700+P680} = 3.59\ eV$. Accordingly, *only one third (35%) of the input energy is transformed into chemical energy*. Figure 4 depicts the light dependent reactions. The main input factors are highlighted in blue boxes, the main output factors in red boxes. Hydrogen (H_2) from the dissociated water (H_2O) from PSII is transported to PSI. There it so to say charges the energy carriers ATP (discharged: ADP) and NADPH (discharged: $NADP^+$). PSI and PSII are powered by photons of different wavelengths (Barsanti, et al., 2006), (Carpentier, 2004).

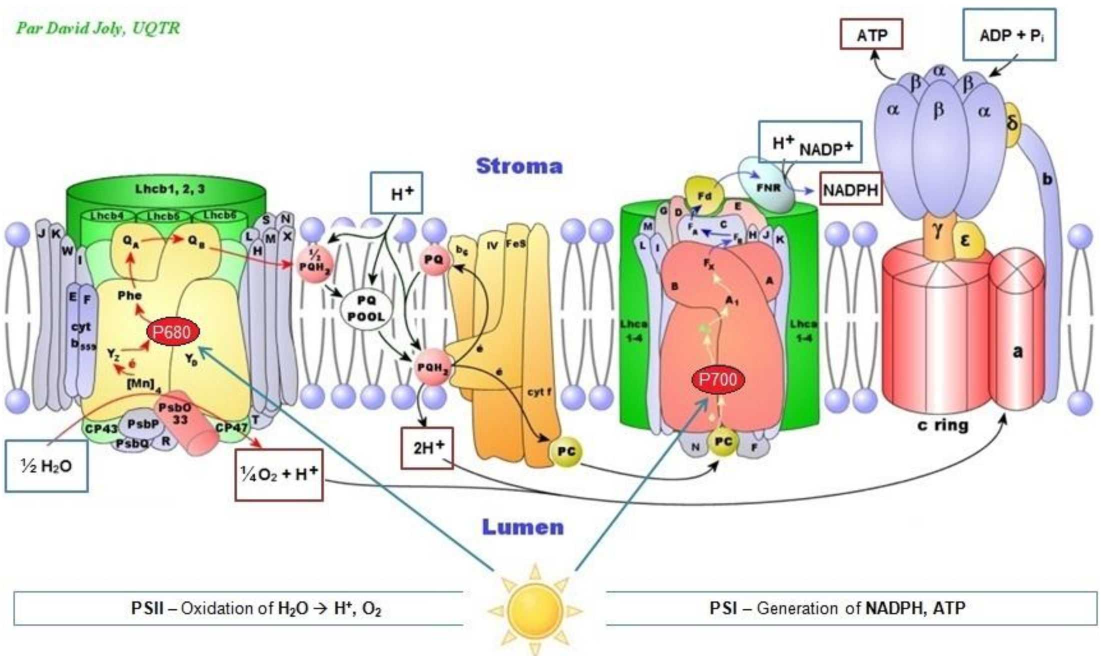

Figure 4: Light dependent complex of photosynthesis
(Carpentier, 2004), adapted

3.1.2.3.1.3 Light Independent Reactions (Calvin Cycle)

The second major group of reactions is the light independent group of reactions, also known as the *Calvin*[16] *cycle*, which is responsible for the final generation of carbohydrates from CO_2 using the energy and reduction capacity, respectively, of ATP and NADPH. These coenzymes are received from the light dependent reactions described in 3.1.2.3.1.2. With respect to the timeline the reactions take place in parallel to the light depending ones. Varying with the organism the light independent reactions take place in the stroma (i.e. a liquid surrounding the thylakoids) for eukarotic algae; for prokaryotic algae they take place in the so called cytoplasm which is enclosed by the cell membrane.

The reactants of the Calvin cycle are CO_2, NADPH and ATP. The cycle itself is structured into three main steps: *Binding of ambient CO_2*, the so called carboxilation, *reduction of CO_2* and the *regeneration of the CO_2 acceptor RuBP*.

In the first phase an acceptor molecule, namely ribulose biphosphahte (RuBP) binds a CO_2 molecule. This reaction is supported by a protein, the so called RuBisCO (ribulose biphosphahte carboxylase oxygenase) which is the most abundant protein in the biosphere because all photoautotroph organisms produce this protein. During this step CO_2 is fixed at no energy transfer. The result of the binding is an intermediate product named 3-PG (3-phosphoglycerate). In the next step the 3-PG is reduced by involving stored energy in the form of ATP and NADPH. The results of this step are a carbohydrate G3P (glyceraldehyde-3-phosphate) on the one hand and the “discharged” energy carriers ADP and $NADP^+$, respectively, on the other hand. The energy carriers are brought back to the thylakoid membrane to be charged again by light depending processes. The carbohydrate in turn is available for following processes forming starch depending on the organism’s needs. Finally, the last step of the Calvin cycle regenerates RuPB so that it can serve as a CO_2 acceptor in the next run of the cycle. This step again consumes energy and is fuelled by ATP. The following equation describes the Calvin cycle after six runs in chemical terms.

$$6CO_2 + 18ATP + 12NADPH + 12H_2O \rightarrow C_6H_{12}O_6 + 18ADP + 18P_i + 12NADP^+ + 6H^+$$

[16] Melvin Calvin won the Nobel Prize in chemistry in 1961 for his work on carbon dioxide assimilation in photosynthesis (Orr, et al., 2008).

3.1.2.3.1.4 Energy Balance

The overall equation for photosynthesis (i.e. production of carbohydrates[17]) and respiration (i.e. consumption of carbohydrates), respectively, can be noted as follows:

$$6H_2O + 6CO_2 \xleftrightarrow{Photosynthesis/Respiration} C_6H_{12}O_6 + 6O_2$$

In case of production water and carbon dioxide are transformed into glucose and free oxygen; during this transformation energy is stored. One mole of glucose[18] contains 686 kcal[19] (that equals 2,870 kJ or 797 W h) of energy. By consuming the stored energy glucose is oxidised to water and carbon dioxide.

As described in chapter 3.1.2.3.1.1 only 5% of the PAR that strikes a single algal cell is transformed into biomass by photosynthetic processes within the cell. The main portion of intracellular losses besides the energy that is needed to fuel the metabolic processes themselves is caused by photorespiration which means that the organism consumes oxygen inverting the production processes (Barsanti, et al., 2006).

3.1.2.3.1.5 Photosynthetic efficiency

The photosynthetic efficiency PE of organisms is defined as the fraction of light energy that is transformed into biomass by organisms. Jan-Willem F. Zijffers found out that the theoretical biomass yield of algae in PBRs under laboratory conditions (i.e. at saturating light intensities) is between 1.5 and 1.8 g per one mole photons. This is based on the fact that the generation of a C-mol[20] biomass which is 21.25 g per mol requires between 11.75 and 14.15 mol of photons when algae is grown on nitrate and urea (Zijffers, et al., 2010). Subject of the research were the species *Dunaliella tertiolecta* and *Chlorella sorokiniana* having a similar elemental composition. Given the average energy content of photons in the PAR bandwidth which is about $220\frac{kJ}{mol}$ the efficiency considering PAR is between 18 and 21%. Taking into account that PAR is about 42% of the total irradiation (Barsanti, et al.,

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[17] Carbohydrates are organic compounds consisting of carbon, hydrogen and oxygen containing twice as many hydrogen atoms as oxygen and carbon atoms, for instance, sugar, starch and cellulose: The chemical formula of glucose is $C_6H_{12}O_6$ (Biology-Online.org, 2007).

[18] The molar mass of glucose ($C_6H_{12}O_6$) is 180.16 g/mol.

[19] The energy unit of one cal corresponds to 4.184 J or W s respectively and is defined as the amount of energy that is needed to raise the temperature of one kilogram water by one degree Celsius.

[20] The molar amount of Biomass that is produced out of one mol of CO_2 is defined as C_{mol} of biomass and has dry weight of $21.25\ g$ and an enthalpy of combustion of $547.8\frac{\mathrm{kJ}}{\mathrm{C_{mol}}}$ (Wageningen UR, 2010).

2006) the efficiency compared to the solar radiation ranges between 7 and 9% (Zijffers, et al., 2010). Figure 5 depicts the light yield and photosynthetic efficiency, respectively.

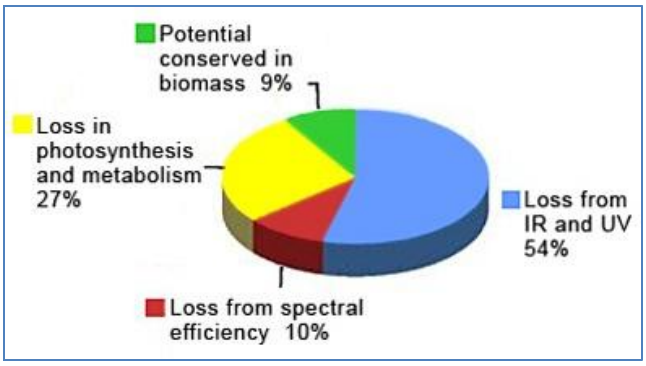


Figure 5: Photosynthetic efficiency for microalgae
(Wageningen UR, 2010), adapted

3.1.2.3.2 Summary

Photosynthesis stands for a very complex series of chemical processes that have developed over millions of years. Its main impact is the composition of biochemical useful energy carriers, i.e. glucose, accompanied by a simultaneous production of free oxygen. The light depending part of the reactions stores light energy in the form of biochemical storage objects handing them over to the light independent series of reactions which consume the stored energy to transform inorganic carbon dioxide into organic mass. The potential for the production of biomass in the form of microalgae ranges between a minimum of *2%* (Barsanti, et al., 2006) and a theoretic maximum of *9% of the available sunlight* (Zijffers, et al., 2010), (Wageningen UR, 2010). Figure 6 shows an overview of the main elements concerning photosynthesis.

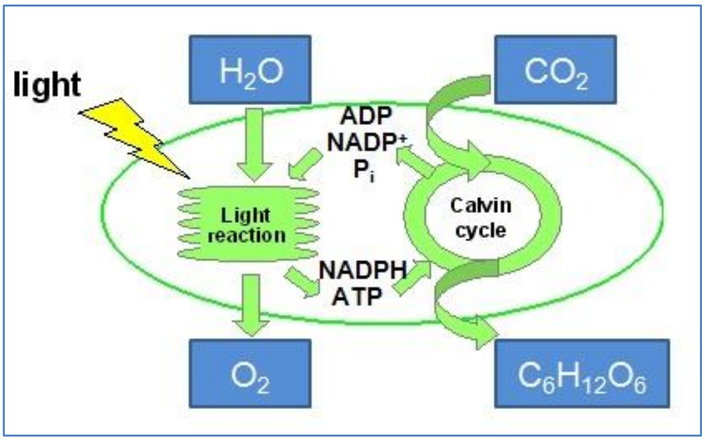


Figure 6: Photosynthesis overview
(Wageningen UR, 2010), adapted

3.1.3 Algae Cultivation and Processing

Algae can grow both in salt or fresh water. Unaffected by the growing medium the cultivation of algae intends to optimise known algae strains and to find new species of algae which are capable of fulfilling different needs in an optimised way. Before algae had come into the focus as a possible energy source algae were cultivated for the production of animal feed and food, for example, in aquacultures as well as for pharmaceutical needs, for instance, as a source for omega-3 fatty acids, carotenoids, pigments, proteins and vitamins (Barsanti, et al., 2006).

3.1.3.1 Growing

Growing algae is a field of increasing interest for researchers and industries around the world; the idea of developing algae as a promising replacement for conventional fuel plants like maize or rapeseed leads to high investments concerning the development of algae cultures with a mass output.

3.1.3.1.1 Nutrition, Water and Environment

The growth of algae depends on some main factors. Of course, photoautotrophic development depends on the required light. The organisms also need H_2O and CO_2 generate hydrocarbons as described in chapter 3.1.2.3. With respect to the expectable yield some limiting factors have to be taken into consideration. Figure 7 shows the biomass yield as a function of PAR intensity and ambient CO_2 concentration. Beyond the light compensation points there is no growth; the metabolic consumption is too high. Increasing the intensity of PAR leads to significantly higher yields.

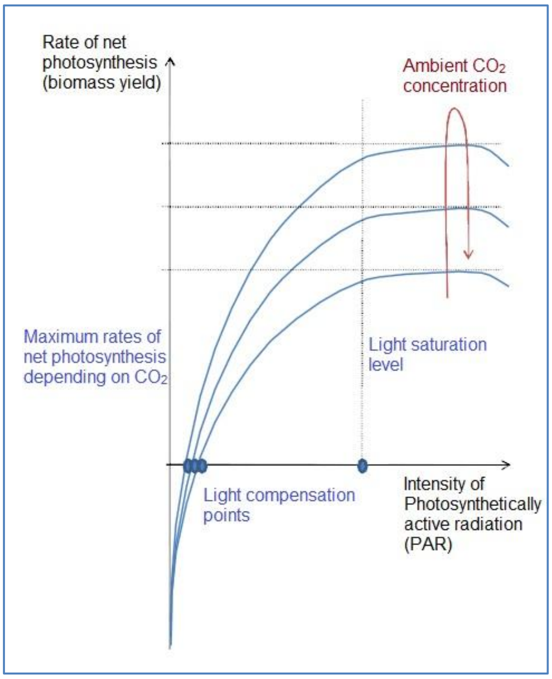


Figure 7: Biomass yield dependent on CO_2 concentration and PAR intensity (Cazzola, 2009)

This tendency can be amplified by higher CO_2 concentrations. Apart from the current greenhouse gas situation it is not very easy to optimise the CO_2

concentration for terrestrial plants. However, it is possible in case of algae cultures by using flue gases or waste water streams. Nutrients such as nitrogen, phosphorus, potassium, silicon and other trace elements or micronutrients[21] supplement the primary input substances. Nitrogen, phosphorus and silicon are so called macronutrients[22]. Silicon is required only for some species, for instance, diatoms (as they have silica cell walls), silicoflagellates and some chrysophytes. Macronutrients are typically required in a ratio of $16N:16:Si:1P$. Carbon is needed in much higher concentrations; the carbon-nitrogen-phosphorus ratio for most species is optimal at values of $106C:16N:1P$ (i.e. a carbon-nitrogen ratio of approximately 4 to 7). A limited carbon dioxide source can be detected when the pH of the culture medium moves up to values of 9 and higher. Ammonium chloride (NH_4Cl) can be source for nitrogen; silicate is added as Na_2SiO_3. The amounts and composition of required trace metals and vitamins (i.e. mainly vitamin B_{12}, thiamine and biotin) depend on the selected species and should be considered when planning large scale culturing of certain species. Beside the mentioned nutrients pH buffers are important to regulate the pH of the medium and keep it at optimum values along algal development (Andersen, 2005 p. 25 et seq.). Waste water streams can offer abundant amounts of nutrients; using this source also saves costs for expensive chemicals. In connection with waste water utilisation it has to be noted that the algae biomass may also consume unwanted chemical components; this must be taken into consideration when planning the algal production chain (Van den Dorpel, 2009). Finally, the pH value in combination with the temperature and the movement or flow of the growing medium has important influences on an optimum development of algae. With respect to the light input it showed out in comparative test installations that direct light is not as effective as indirect and not too intense light. This is because the light absorbing structures within the chloroplasts could be damaged otherwise. Indirect and diffuse light supports the development of algae in an optimum way (Mohr, et al., 2009). Figure 8 shows the environmental actuating variables for algae cultures.

[21] Micronutrients: Substances occurring in concentrations of 0.001 to 0.03% of the dry mass of an organism.
[22] Macronutrients: Substances of which algae contain up to 5% of the dry mass (Hofbauer, 2009).

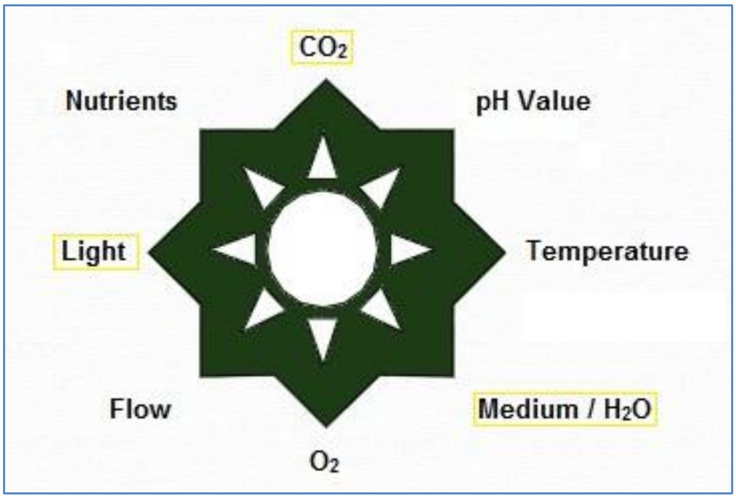


Figure 8: Environmental actuating variables for microalgae
(Van den Dorpel, 2009), adapted

3.1.3.1.2 Optimised Freshwater and Seawater Culture Media

As discussed in chapter 3.1.2.2 there is an abundant number of different algae species. The algae related research has developed a huge variety of optimised freshwater and seawater growing media to cultivate certain algae strains. Many of the recipes can be found in literature and on internet sites. The data lists nutrients, optimum pH values and trace elements along with algae strains the recipes apply to. Annex 3 lists web resources concerning culture collections and recipes.

3.1.3.1.3 CO_2 Sources

Algae require between 1.7 – 2.8 kg carbon dioxide per kilogram algae mass (Van den Dorpel, 2009). In order to optimise algal development within the culture additional CO_2 has to be supplied to the growing medium. Generally, it has to be stated that algae are not capable of capturing CO_2 contained in the flue gas of coal fired power plants (CPP); even small scale CPPs would need thousands of hectares of algae to absorb the generated CO_2. The global potential for CO_2 captured by algae cultures with respect to CPPs is located below 1%. When it comes to the dimensioning of nutrients in general and CO_2 in particular it has to be pointed out that carbon dioxide is mainly needed during periods of maximum algae growth (i.e. on sunny summer days). At night time and during the winter season the needed amounts of CO_2 are significantly lower. Ideal CO_2 sources for algae cultures are biomass power plants, municipal solid waste processes (i.e. landfills) or municipal waste water treatment plants. At all, waste water is an ideal supplier concerning CO_2 and nutrients like phosphorus, nitrogen etc. (Benemann, 2009).

3.1.3.1.4 Growth Inhibition by Disadvantageous Conditions

As discussed in 3.1.2.3.1.2 photosynthetic processes transform solar light energy into chemical energy while setting free oxygen. Research has found out that, depending on the selected algae strain, the oxygen concentration within the growing medium can reach values of about $40\frac{mg}{L}$ (i.e. 450% of saturation[23] at 20 – 25 °C). However, some algae strains show inhibited growth if the oxygen concentration in the growing solution gets too high. This phenomenon can be observed in closed PBR systems where oxygen tends to accumulate within the growing medium. In most cases oxygen related growth inhibition is accompanied by other growth inhibitors like temperature. The lipid production depends on the available carbon and on the activity of the involved enzymes. It has been found out that starving algae of nutrients may induce a stronger lipid concentration. For instance, a deficiency of nitrogen can lead to a lipid allocation; on the other hand missing nitrogen may disturb the photosynthetic binding and transformation of CO_2. Another method of enhancing a fast lipid production has been investigated by the ASP (i.e. the Aquatic Species Program) of NREL, namely, the method of silicon starvation. For example, this method led to a 60% increase of lipid of diatom species (i.e. *Navioua pelliculosa*) content within a silicon starvation period of about 14 hours (Oilgae.com, 2010).

3.1.3.1.5 Temperature

With respect to algae development temperature is an important factor. It affects the function and efficiency of intracellular enzymes. Microalgae can grow at a wide range of different temperature conditions. Accordingly, algae can be classified by their optimum temperature area. The following table lists three different classes and some details on each class. The data is taken from Wageningen University (Wageningen UR, 2010). Different temperature conditions may lead to different oil concentrations of the species. Culture temperature and light intensity influence the algal development at the same time. Therefore it is essential to select the best adapted species for growing algae at certain conditions.

[23] "Oxygen saturation is expressed as the percentage of dissolved O_2 concentration relative to that when completely saturated at the temperature of the measurement depth. As the temperature increases, the concentration at 100% saturation decreases. […] The DO (i.e. dissolved oxygen) concentration for 100% air saturated water at sea level is 8.6 mg O_2/L at 25 °C and increases to 14.6 mg O_2/L at 0 °C" (Munson, et al., 2007).

Table 2: Temperature related classification of algae
(Wageningen UR, 2010), adapted

Class	Characteristics	Examples
Psychrophilic algae	Adapted to cold water; growing at 0 °C and below (applies to salt water) with optimum slightly above 0 °C.	*Nitzschia* and *Amphiphrora* (diatoms); *Chlamydomonas* (cryptomonad genus); *Chlorella* (green alga)
Thermophilic algae	Adapted to warm water; growing at up to 75 °C.	*Synechococcus* and *Synechocystis* (cyanobacteria)
Mesophilic algae	Algae with growing maximum between the listed extrema; some algae are very thermo-tolerant, see examples. Most algae suitable for industrial purposes have growing maxima at about 25°C.	*Chlorella sorokiniana* (grows from 5 °C to 45 °C at an optimum at 35 °C).

3.1.3.2 Cultivation Systems

When it comes to culturing equipment there are two main forms of growing systems. On the one hand it is the *open pond* technique on the other hand it is the so called *photo bio reactor (PBR)* technique.

3.1.3.2.1 Open Pond Systems

Open pond systems simulate natural water bodies. In addition, technical equipment is added to optimise the growing circumstances. Optimisation can be achieved by stirring the water with paddles in order to enhance the CO_2 input into the medium and to reach a steady flow which is important for the distribution of nutrients as well as for the later harvesting process. Measuring systems are applied to control the growth of algae within the pond. Open ponds often are constructed in the form of meanders so that the water area can be as small as possible and that an optimum flow of the medium can be achieved. It is also possible to design circular open ponds. Open pond systems have been subject of research in pilot systems since the 1960's also in combination with waste water treatment by Berkeley Engineering Labs and by the Aquatic Species Program (ASP) of the U.S. DOE NREL (National Renewable Energy Laboratory, Facility of the Department of Energy) (Benemann, 2009). Waste water delivers nutrients in abundant amounts. CO_2 can be bubbled into the water to support algal development. Practical examples and pilot plants exist in numerous cases. The systems are relatively simple and low priced. Ponds are set up easily; the stirring equipment is simple and robust. However, there are some obstacles, for instance, the high dependency on environmental conditions such as changing temperature and climate conditions. Another issue is the possible contamination with local and unwanted algae species or with organisms which feed off the grown algae. As a matter of fact the physical and chemical conditions of the growing medium cannot be controlled precisely. The systems are characterised by a high evaporation and therefore need high amounts of water inflow. Of course, in the case of waste water treatment facilities this is not disadvantageous. For an ideal light and water supply these systems are often placed in sunny regions with access to water (i.e. by the sea or near rivers or waste water sources). The following pictures give examples for open pond systems. Annex 5 provides a guide concerning large scale open pond systems.

Picture 3: Raceway open pond system (Wijffels, 2009)

Picture 4: Circular open pond system (Benemann, 2009)

3.1.3.2.2 Practical Example: Open pond – legal situation in Lower Austria

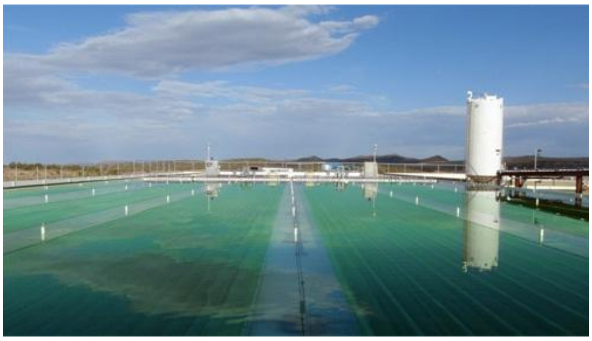
Open pond systems can be set up relatively easy. For a small scale testing plant it is only necessary to have access to an open area where a pond can be placed. The pool should be sealed in order to avoid losses of the culture medium. Depending on the system design such a system can be built without permissions of local authorities. However, there is a notification requirement. The permission depends on the water logistics and the expected impacts on the nature. The key factor for operating an open pond in Lower Austria without any permission is that there is no water outlet. It is allowed to supply the pool with fresh water (i.e. ground water or water from a nearby body of water) to compensate evaporation losses. In order to fulfil the notification requirement an informal document has to be addressed to the local authorities. It should explain the project and contain a schema of the planned pond system. For project start ups existing infrastructure such as closed down water treatment ponds may be reused without any complications. According to the information from local authorities (i.e. Central Administration, district Melk, Lower Austria) an open pond project located in Lower Austria has to be planned in consideration of certain prerequisites. The most essential information regards water source, water overflow and contact of the pond with the ground water system, respectively. More details can be found in Annex 4 of this paper.

3.1.3.2.3 Photobioreactor (PBR)

A photobioreactor is technical facility for growing algae in a highly controlled way. It is defined as a closed growing system carrying a liquid substrate containing all necessary ingredients for algae to develop in an optimised way. PBRs descend from laboratory and small scale systems which were originally developed to study algae species or to produce high priced algae products such as pharmaceutical commodities. The first historic algal mass culture project (growing *Chlorella*), however, was realised in form of plastic bag-type photobioreactors on the roof of the MIT building back in the 1950's. In contrast to open pond systems the substrate is isolated from the environment and circulates within the system. As a result, the CO_2 and nutrient concentration as well as temperature and the flow velocity etc. can be regulated according to the needs of the cultivated algae species. These systems allow a kind of managed algae development and overcome environmental dependencies and contaminations. A higher surface-to-volume ratio leads to a higher cell and biomass density, respectively, as well as to high temperatures on days with intense solar radiation. To avoid energy consuming cooling this fact has to be taken into consideration when selecting algae species for a certain PBR. However, the prices for PBRs are relatively high. Consequently, there are only small numbers of industrial scale facilities. The systems are equipped with different devices moving the water within the system (i.e. with the help of mechanical pumps or by taking advantage of hydrostatic pressure to effect a circulation) (Mohr, et al., 2009), (Van den Dorpel, 2009).

3.1.3.2.3.1 Tubular PBR

Tubular PBRs consist of (vertically or horizontally allocated) meandering tube systems which are exposed to the sunlight. The tubes are made from diaphanous materials in order to deliver light into the growing solution. The tubes materials can be solid or flexible. The tubular structure provides flexibility with respect to the layout of the PBR; furthermore, it supports a constant substrate flow. Yet, it hinders an easy outtake of the produced oxygen on the one hand and the consistent intake and dispersion of nutrients and CO_2 on the other hand. Picture 5 and Picture 6 show examples for different tubular PBRs:



Picture 5: Tubular PBR placed in a water pond
(Solix Biofuels, 2009)

Picture 6: Tubular PBR vertically allocated
(Cazzola, 2009)

3.1.3.2.3.2 Flat Panel PBR

Flat panel PBRs consist of see through panels forming a flat box maximising the area which is exposed to the sunlight. Again, between the front and back cover meander like structures guide the moving algae substrate The PBRs are placed vertically and can be equipped with rotating mechanisms to regulate the light intake during day time. On the bottom of the panel CO_2 is brought into the system, on the top oxygen is released (Mohr, et al., 2009). Panels can be placed in a stack providing an efficient usage of the space required by the system. Figure 9 shows a schema of a flat panel PBR. The algae grow while the medium proceeds through the meanders; the gas flow (i.e. CO_2 input and O_2 output) is constant.

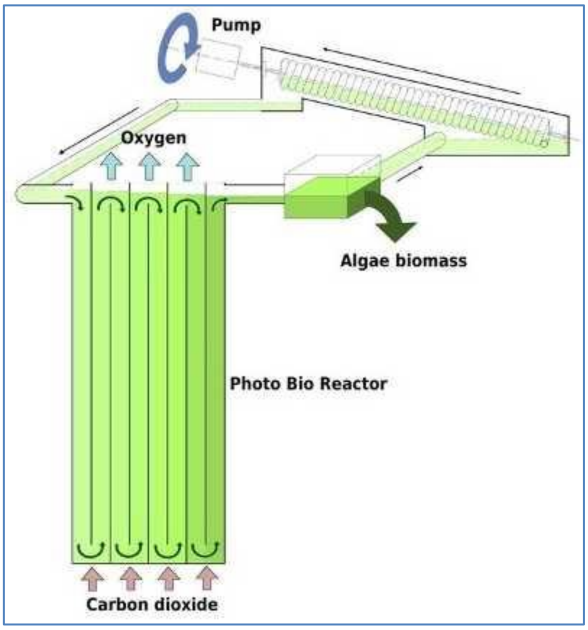


Figure 9: Flat panel growing system
Ecoduna, Austria (Mohr, et al., 2009)

3.1.3.2.4 Energy Consumption of Growing Systems

Depending on the applied system design the energy efforts may be significant. In open pond systems the stirring paddles need energy to be operated. PBRs show a higher energy intake due to pumping devices; it is even higher especially when the substrate is temperature controlled. Generally, heating is less energy intensive than cooling. Most algae which are used for energy purposes have an optimum output rate when growing at 20 – 30 °C (see also 3.1.3.1.5). Figure 10 shows a schematic growing and harvesting system indicating energy consuming infrastructure elements.

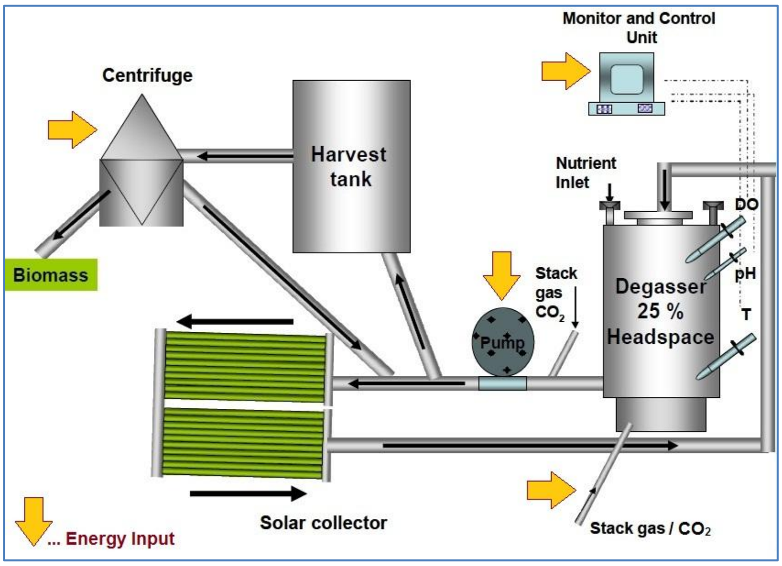


Figure 10: Schema of algae growing and harvesting system (Wijffels, 2009), adapted

3.1.3.2.5 Summary and Comparison

Generally, the current situation in the development of algae growing systems for energy purposes shows a mixed picture. Current plants mostly base on the research in the field of non energy related algae usage. The following table shall give a comparative overview on the described principles.

Controlling the temperature of the medium is important for all systems. Open pond systems do not allow a precise temperature control of the medium; the pool behaves like natural waters. Closed systems tend to heat up when exposed to direct sunlight on sunny days because of the high surface-volume ratio. To avoid too much cooling efforts algae should have their optimum growth at rather high temperatures when cultivated in photobioreactors (Wageningen UR, 2010). Some tubular PBR installations are equipped with tubes which are embedded in water ponds to reduce the cooling expenses (Solix Biofuels, 2009). Table 3 gives a comprehensive comparative picture of advantages of open ponds vs. PBRs.

Table 3: Open pond systems vs. PBRs
(Benemann, 2009), (Oilgae.com, 2010), adapted
Legend: OP… Open ponds; PBR… Photobioreactors

Characteristics	Comparison	Notes
Contamination risks	OP > PBR	
Productivity	OP < PBR	PBR productivity is higher at vertical allocated installations; productivity is defined as biomass yield per hectare
Space required	OP ~ PBR	Depends on productivity
Water losses	OP ~ PBR	PBRs need cooling
CO_2 losses	OP ~ PBR	Depends on chemical situation in algae medium (pH, etc.)
O_2 inhibition	OP < PBR	Especially tubular PBRs have problems with O_2 outtake
Process control	OP < PBR	Open ponds have to cope with weather impacts
Biomass concentration	OP < PBR	Depends on depth of water; 2 – 10 fold
Operating costs	OP << PBR	Costs of PBRs up to 10 times higher

3.1.3.3 Harvesting, Concentration and Drying, Extraction of Oil

Harvesting algae represents the process of separating algae (i.e. algae paste) from the growing medium. The output of a PBR, for instance, consists of a large percentage of water and a rather small percentage of biomass. Caused by the continuous growth of algae harvesting has to be organised different compared to the gathering of other energy crops: harvesting algae is an ongoing process. Furthermore it is essential adapt the harvesting method to the used algae species which differ in size from unicellular structures with a size of some microns to groups of cells of up to some millimetres in size. Depending on the later usage of the biomass there are different methods to collect the biomass. Especially if the contained oil is needed in a pure form for subsequent production steps the wet biomass has to be separated from water and this way concentrated for most of the affiliate transformation processes. Figure 11 shows the process diagram of growing and harvesting algae combined with output materials in a schematic overview.

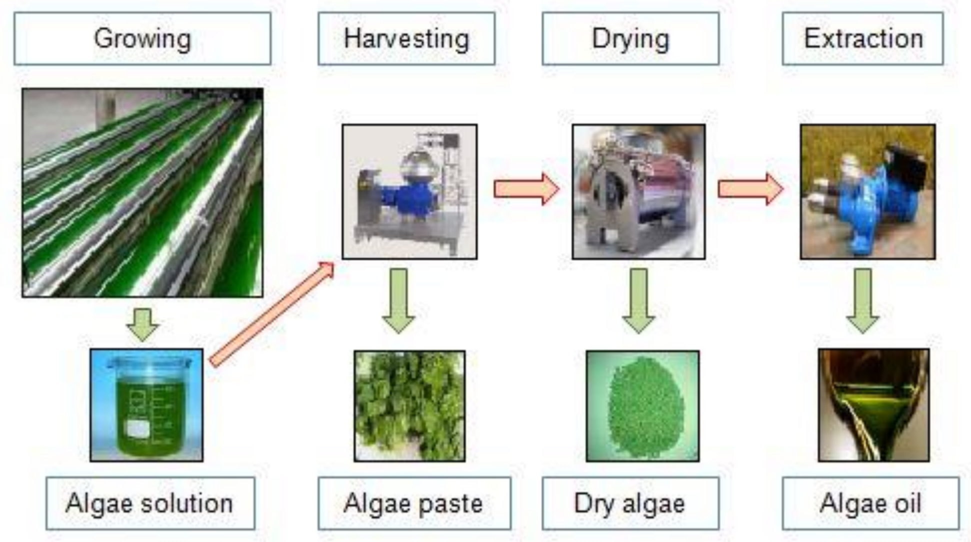


Figure 11: Algae harvesting, drying and extraction
(Van den Dorpel, 2009), adapted

The following classification summarises the most prominent current harvesting techniques (Oilgae.com, 2010), (Van den Dorpel, 2009), (Benemann, 2009).

3.1.3.3.1 Sedimentation

This approach is used with algae which tend to settle down on the bottom of the growing medium; it is mostly used with diatom species having a relative high density (i.e. this is caused by their silica cell wall) combined with a low motility. Most waste water treatment systems working with algae use this method. This way the biomass can be collected at the bottom of the growing ponds.

3.1.3.3.2 Bio Flocculation and Chemical Flocculation

Bio flocculation is the spontaneous forming of flocs which occurs at a lack of CO_2 in high rate ponds equipped with mixing paddle-wheels. Subsequently, the flocs may settle down on the bottom of clarifier ponds. Bio flocculation is significantly more cost saving compared to a flocculation based on chemical binding agents added to the algae culture to build algal flocs. Examples for chemicals causing flocculation are alum[24] and ferric chloride. Beside the cost factor it is difficult to remove the chemicals from the harvested biomass later on.

[24] Alum stands for trivalent sulphates of metal such as aluminium, chromium (Oilgae.com, 2010).

3.1.3.3.3 Filtration

Filtration of an algae-water substrate is a method to concentrate the biomass. It is done by different types of machinery such as rotating drums, disc type or belt type filters using different filtering materials in a continuous way. This can be done in one or in multiple stages. Filtration systems have in common that the medium containing algae biomass is led through a filtration medium that retains most parts of algal mass and separating it from the growing medium. For very small algae such as Dunaliella it is possible to use filters coated with a layer of algae which are lager in size, for instance, Spirulina[25].

3.1.3.3.4 Flotation

Contrary to sedimentation flotation tries to cause the algae cells to build froth and accumulate on the surface of the culture. It is done by bubbling in air by tubes inside the growing water. This process can be supported by adjusting the pH value of the culture medium depending on the used species. Some methods also use chemicals causing flocculation in combination with air bubbles causing similar problems as discussed in section 3.1.3.3.2. This method is an established solution for sewage treatment plants.

3.1.3.3.5 Centrifugation

This method uses vertical allocated centrifuges separating algae from the culture medium. Biomass can be collected at the bottom of the centrifuge. It can be problematic that cell walls are destroyed by the mechanical stress. To make use of this fact centrifuges can also be used in combination with so called homogenisers to separate algae from oil contents which are, for example, transformed into biofuels.

3.1.3.3.6 Drying

The drying of algae is an essential step in order to get a storable product. In that sense algae paste which is the output of the various harvesting methods has to be dried to a moisture content of about 10 – 15%. With respect to the overall production efficiency finding an energy saving drying method is crucial for the utilisation of algae. *Drum drying* and *flash drying* are industrial ways of decreasing the moisture content. They can require a very high percentage of up to 50 – 60% of the energy stored within biomass. Strains with high energy content and the usage of process heat which is generated by the recycling of otherwise unused algae residues may

[25] The algae based filtering system is described at http://www.patents.com/means-recovering-algae-4465600.html (June 3, 2010).

help to overcome these obstacles with respect to efficiency losses (Cazzola, 2009). Solar powered drying and sun drying are very economic alternatives.

3.1.3.3.7 Extraction of Oil

The extraction of algae oil is the process of separating the stored lipids from the concentrated algae biomass. Algae oils are used in a variety of applications: from nutrition (i.e. the use of omega-3 fatty acids) to bio crude oil for the production of biodiesel (transesterification). De-oiled algae residues in the form of press cake can be used in further processes such as anaerobic digestion to produce methane. The CO_2 which is set free along with digestion processes can be recycled by feeding it back to the algae culture. Depending on the algae species the extraction can be done by *pressing* with the help of presses of different configurations (i.e. screw presses, piston driven presses or expeller presses). Pressing can get up to 70% of the available oil out of the biomass. In addition, it is the cheapest way of extracting oil. Alternatively, the oil extraction can be done by adding *chemical solvents* such as hexane. This option is critical because hexane is a neurotoxin. *Super critical oil extraction* is a very expensive method to rapidly dissolve the oil using carbon dioxide at critical pressure and temperature (i.e. CO_2 in an almost liquid phase). There some further methods such as *enzymatic extraction*, *osmotic shock extraction*, *ultrasonic methods* and combinations of methods (Van den Dorpel, 2009), (Oilgae.com, 2010).

3.1.4 Biomass

Algal biomass is the result of algae growth. As algae do not have stems and roots algae biomass is a rather homogenous mass. This section depicts the main components of algae biomass as well as the productivity and yields for algae. At the beginning, a list of some algae strains may give an idea of how the huge variety algae can be found. The list concentrates on algae with high oil and starch concentrations which is the base for the utilisation as an energy source.

3.1.4.1 List of Strains

The following list of some strains gives an exemplary overview of some species which are currently investigated by researchers concerning their ability to be grown at high scale for mass-oil (i.e. biodiesel) production. The data is taken from “Oilgae Report Academic Edition” (Oilgae.com, 2010).

3.1.4.1.1 Strains with High Oil Content Suitable for Mass Production

Algae species may allocate lipids which can be collected as algae oil. The following list characterises some strains with high oil contents.

Table 4: Algae with high oil content
(Oilgae.com, 2010), adapted

Species	Oil content [% of dry weight]	Remarks
Botryococcus braunii	25 – 75	Green alga; slow reproduction of 72 hours; fast reproduction (2 days) only at certain circumstances: ambient temp. 23 °C, light intensity: 30 – 60 W/m², photoperiod: 12 hours light, 12 hours dark, salinity of 8.8%; forms oil droplets.
Dunaliella Spp.	20 – 25	Green alga; grows in wide range of marine and freshwater habitats, mainly in water bodies containing more than 10% salt.
Dunaliella tertiolecta	40	Unicellular alga; fast growing, high CO_2 consumption.
Euglena gracilis	14 – 20	Belongs to the Euglena species – protists that can eat food like animals (partly heterotrophic) and produce food like plants (partly autotrophic); lives in fresh water, sea water and soil; optimum carbon dioxide concentration of 4%; optimum oxygen concentration: 20%; can be acquired from many public sources.
Isochrysis galbana	25 – 30	Microalga (flagellate); used as food in the aquaculture industry; has no established genetic system; growth rate of 0.6 doublings per day (40 hours for one doubling).
Nannochloropsis salina	25 – 30	Small green alga; used in the aquaculture industry for growing small zooplankton.
Neochloris oleoabundans	35 – 54	Microalga (Chlorophyceae); has many similarities with higher plants (for instance, break down of nuclear envelope at mitosis; has no established genetic system; growth rate of 0.6 doublings per day (40 hours for one doubling); grown at pH of 7.01.
Phaeodactylum tricornutum	20 – 30	Diatom with sequenced genome; is being studied to grow without light.
Prymnesium parvum	22 – 38	Known as “golden algae”; toxic, flagellated alga (haptophyte); leads to fish kills (little effects to humans); toxins are produced if physiological stress is applied (N and P depletion); grows in salinity range of 0.1 – 10%, accepts temperature areas of 2 to 30 °C; grows at pH as low as 5.8 (higher values are better); can use a wide range of nitrogen sources such as ammonium, nitrate, amino acids and creatine; problematic in large quantities because of the toxicity.
Scenedesmus dimorphus	16 – 40	Unicellular alga (Chlorophyceae); one of the

		preferred species for oil yield for biodiesel; obstacles: heavy, forms thick sediments if not kept in constant agitation; optimal growth temperature: 30 – 35 °C; can be acquired from a variety of public sources.
Tetraselmis chui	40 – 45	Marine unicellular alga (large green flagellates); very good feed for larval shrimp; has no established genetic system; growth rate of 0.6 doublings per day (40 hours for one doubling).
Tetraselmis suecica	20 – 30	Green alga (marine phytoplankton); utilised in aquaculture.

3.1.4.1.2 Strains with High Carbohydrate Content

The following table lists some strains with a high starch and sugar content.

Table 5: Algae with high carbohydrate content
(Oilgae.com, 2010)

Species	**Carbohydrates** [% of dry weight]	**Lipids** [% of dry weight]
Scenedesmus dimorphus	21 – 52	16 – 40
Spirogyra sp.	33 – 64	11 – 21
Euglena gracilis	14 – 18	14 – 20
Prymnesium parvum	25 – 33	22 – 38
Porphyridium cruentum	40 – 57	9 – 14
Anabaena cylindrica	25 – 30	4 – 7

3.1.4.2 Productivity and Yields: Algae vs. Energy Crops

The high net primary productivity (i.e. the rate at which an ecosystem accumulates energy or biomass of algae compared to plants is considered to be significantly higher. The *photosynthetic efficiency (PE) of plants is about 1%* (3 – 4% in the best cases, for example, sugar cane). About 10% of the energy stored by plants can be exploited. This means that only 0.1% of the solar energy may be transformed into useful energy (Hofbauer, 2009). *Algae have a photosynthetic efficiency* of at least 2 to maximal 9% (see 3.1.2.3.1.5) at an average of *about 5%*. In addition, the speed of growth is considerably higher; algae biomass doubles within a few days. The combination of higher efficiency and the fast growth makes algae remarkably more productive than plants (i.e. for some algae strains photosynthetic efficiency as well as oil allocation is at least an order of magnitude higher).

The following table gives an overview on evaluated oil yields of algae compared to other fuel crops. The data is taken from John R. Benemann. The higher value for microalgae is the theoretical yield at a maximum efficiency of algae growth. The lower value is the reachable potential after long-term research and development. In near future about the half (i.e. 30.000 litres per hectare and year) are realistic (Benemann, 2009), (Cazzola, 2009), (Oilgae.com, 2010).

Table 6: Oil yields per hectare and year compared with energy crops
(Benemann, 2009), (Cazzola, 2009), (Oilgae.com, 2010), adapted

Oil yields	Litres [per hectare and year]	Notes
Soybeans	400 – 900	
Sunflower	800	
Rapeseed	900	
Canola	1,600	
Jatropha	2,000	
Palm Oil	4,500 – 6,000	
Chinese tallow	4,500 – 9,000	
Microalgae	Near future: 30,000 Long-term R&D: 60,000 Max. efficiency: 120,000	The higher value is related to the maximum efficiency; the medium value is based on long-term R&D; the lower value is realistic for near future

Biomass yields show similar tendencies. Terrestrial plants have a typical biomass yield of below $10\ g/m^2/day$; with an average of at least $20\ g/m^2/day$ algae biomass yields are twice as high.

3.1.4.3 Components and Fractions

The relevance of algae biomass for energy purposes is mainly driven by its chemical components. Beside energy related use some chemicals may be recycled or used for other purposes such as food or pharmaceutical applications. The following table depicts the chemical components (i.e. proteins, carbohydrates and lipids) of some algae strains. The data is taken from Oilgae.com (Oilgae.com, 2010) and Peter van Dorpel, AlgaeLink (Van den Dorpel, 2009). It can be seen that the lipid (i.e. oil) content varies around 20%. In algae cells lipids as well as hydrocarbons have the functions as membrane components, storage systems, metabolites[26] and energy sources.

[26] Metabolite: "Any substance produced by or involved in metabolism or metabolic process"; it can also be an end product as a result of metabolism (Biology-Online.org, 2007).

Table 7: Components of algae strains: proteins, carbohydrates and lipids (Oilgae.com, 2010), (Van den Dorpel, 2009), adapted

Algae strain	Protein [% of dry wt.]	Carbohydrates [% of dry wt.]	Lipids [% of dry wt.]	Nucleic acid [% of dry wt.]
Fresh water algae				
Scenedesmus obliquus	50 – 56	10 – 17	12 – 14	3 – 6
Scenedesmus quadricauda	47	-	1.9	-
Scenedesmus dimorphus	8 – 18	21 – 52	16 – 40	-
Chlamydomonas reinhardii	48	17	21	-
Chlorella vulgaris	51 – 58	12 – 17	14 – 22	4 – 5
Chlorella pyrenoidosa	57	26	2	-
Spirogyra sp.	6 – 20	33 – 64	11 – 21	-
Dunaliella bioculata	49	4	8	-
Euglena gracilis	39 – 61	14 – 18	14 – 20	-
Prymnesium parvum	28 – 45	25 – 33	22 – 38	1 – 2
Tetraselmis maculata	52	15	3	-
Porphyridium cruentum	28 – 39	40 – 57	9 – 14	-
Spirulina platensis	46 – 63	8 – 14	4 – 9	2 – 5
Spirulina maxima	60 – 71	13 – 16	6 – 7	3 – 4.5
Anabaena cylindrica	43 – 56	25 – 30	4 – 7	-
Marine algae				
Isochrysis sp. (strain T.ISO)	44	9	25	
Dunaliella salina	57	32	6	-
Synechoccus sp.(cyanobacteria)	63	15	11	5
Pavlova lutheri	49	31	12	
Isochrysis galbana	41	5	21	
Tetraselmis suecica	39	8	7	

As an example the following table lists the substances which are included in algae mass with the mass of 1,000 kg from an output oriented perspective. The table shows possible utilisation paths for an economic and integrated exploitation; furthermore, it gives price indications for the single fractions. The data is taken from René H. Wijffels (Wijffels, 2009). Non energy related utilisation of chemical substances achieves rather high income; this way the high production costs can be compensated with some minor losses of yield.

Table 8: Chemical substances and fuel contained in algae biomass (Wijffels, 2009)

Substance	Mass [kg]	Possible utilisation path	Current prices [€/kg]
Biomass	**1,000**		
Lipids	400	100 kg for chemical industry 300 kg for energy (fuel)	2.00 0.50
Proteins	500	100 kg for food	5.00

		400 kg for feed	0.75
Polysaccharides	100		1.00
Nitrogen [N] (contained)	70		2.00
Oxygen [O_2] produced	1,600		0.16

Beside the fractions of proteins, carbohydrates and lipids the elementary composition of biomass materials is essential for further utilisation processes. Table 9 lists the element fractions of some algae strains compared to maize.

Table 9: Element fractions of algae strains compared to maize (ECN-Biomass, 2010)

Element	Spirulina [% of dry wt.]	Monodus subterraneus [% of dry wt.]	Other microalgae strain [% of dry wt.]	Maize [% of dry wt.]
C	43.9	54.8	52.7	44.6
H	6.86	6.67	7.22	5.37
O	34.5	23.5	28.9	39.6
N	6.54	6.66	8.01	0.41
S	0.43	0.44	0.49	0.05
Cl	-	0.054	0.177	1.48

In comparison with maize it gets obvious that algae substrates mainly differ with respect to nitrogen (N) and sulphur (S); both elements have higher fractions. The hydrogen fractions are slightly higher but still below 10%; more than half of the biomass substrate consists of carbon; at some strains the concentration is even higher. However, algae's chlorine concentrations generally are very low if compared to maize. The significantly higher nitrogen fractions of algae can cause problems in case of later use in fermenters because methanogenesis is hindered by too high nitrogen concentrations; higher nitrogen fractions are also difficult at direct combustion because of higher NO_x (i.e. nitrogen oxide) concentrations within the flue gases (Ortner, 2010).

3.1.5 Energy Content of Biomass

The mass specific energy content of biogenic fuels is defined by the so called calorific values and heating values, respectively. The higher heating value (*HHV*, *Ho*, *gross calorific value*, unit: kJ/kg) is defined as the amount of heat which is released during the complete combustion of a certain biofuel; in addition it contains the evaporation heat of the contained water at a reference temperature of 25 °C. The *lower heating value* (*LHV, Hu*, also known as *net calorific value*, *net CV*, unit: kJ/kg), on the other hand, defines the heat that is released during the total combustion of a certain biofuel; the evaporation energy is not included. In general, the LHV value is lower than the HHV value. The net calorific value of a certain type of biofuel is significantly more dependent on the water content of the fuel than on the type of fuel. It can be stated that the difference between HHV and LHV decreases with the hydrogen and water fraction of the fuel substrate. Under practical conditions no biofuel is free of water. As a matter of fact the values are given for the dry matter in order to get comparable magnitudes. Typical LHV values for biomass range between 15.8 MJ/kg (straw) and 21.4 MJ/kg (rape). Wood based fuels range between 18 and 19 MJ/kg (Hofbauer, 2009). Table 10 shows calorific values for some algae strains compared to typical energy crops. The values reference to dry substances and are taken from the "Biomass datapage Phyllis" (ECN-Biomass, 2010).

Table 10: Calorific values for some biomass materials
(ECN-Biomass, 2010)

Biomass material	**HHV** dry material, [MJ/kg]	**LHV** dry material, [MJ/kg]
Spirulina	19.818	**18.321**
Microalgae	23.480	21.904
Monodus subterraneus[27]	26.357	**24.901**
Rape	21.604	20.187
Wheat straw	18.416	17.206
Maize	17.690	**16.509**

It can be seen that algae have even higher calorific values than rape which has the highest values compared to other energy crops. This fact may be caused by the homogenous cellular structure of algae.

The lower heat value of biomass can be calculated based on the elementary composition of the biomass substance by using *the formula or Boie.* The lower case letters indicate the percentage of the corresponding chemical elements percent of the mass. The sum of the fractions is 1. (Ortner, 2009):

$$Hu = 34{,}835 * c + 93{,}870 * h + 6{,}280 * n + 10{,}465 * s - 10{,}800 * o - 2{,}440 * H_2O$$

The calculated value defines the kilojoules per kilogram of mass (i.e. kJ/kg) of the particular fuel. It gets obvious that the water as well as the oxygen contained in the substance reduces the heat value. This is caused by the fact that the contained water has to be evaporated during thermal conversion; the evaporation energy is

[27] "Monodus subterraneus is a fresh water alga which is surrounded by a cell wall. This algae produce eicosapentaenoic acid (EPA), an omega-3 unsaturated fatty acid" (NOD - Dutch Research Database, 2009). Monodus belongs to the class Xanthophyceae (see Table 1).

reduced from the net energy yield of the biomass fuel. Flue gas condensation is necessary to get back that energy (see higher heating value). For a verification of the given magnitudes of lower heat values (see Table 10) the formula of Boie is to be applied to the element fractions of different biomass substrates (see Table 9).

Table 11: Calculated values for Hu (Formula of Boie)

Substrate	Calculated vs. given value [MJ/kg]	Notes
Spirulina	Calculated value: **18.461** Given value: **18.321**	Hu = 34,835 * 0.439 + 93,870 * 0.0686 + 6,280 * 0.0654 + 10,465 * 0.0043 -10,800 * 0.345 – 2,400 * 0
Monodus subterraneus	Calculated value: **23.277** Given value: **24.901**	Hu = 34,835 * 0.548 + 93,870 * 0.0667 + 6,280 * 0.0666 + 10,465 * 0.0044 -10,800 * 0.235 – 2,400 * 0
Maize	Calculated value: **16.331** Given value: **16.509**	Hu = 34,835 * 0.446 + 93,870 * 0.0537 + 6,280 * 0.0041 + 10,465 * 0.0005 -10,800 * 0.396 – 2,400 * 0

3.1.6 Conversion Paths

This chapter concentrates on conversion paths of algae biomass into secondary energy (see chapter 1). Conversion processes aim to make use of the stored chemical energy by transforming it into technically useful types of fuel. Generally, every conversion process is accompanied by conversion losses such as thermal losses. This fact is defined by the first and the second law of thermodynamics and can be described with the use of the terms *exergy* and *anergy*. Firstly, energy consists of both properties:

$$Energy = Exergy + Anergy.$$

Secondly, exergy, also known as *available energy*, is defined as energy that can be transformed into any other form of energy depending on the environmental conditions of a system. In other words it is the maximum useful work available during a process. Finally, anergy is defined as energy that cannot be transformed into exergy. According to the first law of thermodynamics the sum of anergy and exergy remains constant during conversion processes. The second law of thermodynamics states that in all irreversible processes, for instance, during combustion of substances portions of exergy are transformed into anergy causing a heat change within the system. Frictional warming during mechanical processes is another example for anergy. Only in the case of (theoretically thinkable) reversible processes the sum of the amounts of exergy involved in the process is kept at constant levels. The transformation of anergy into exergy, however, is not possible[28]. Following the second law any real process is irreversible. This means that there is no technical or natural process at all that can be fully reversed with all its effects. The principle of irreversibility shows up the limitations with respect to the process direction; it also explains conversion losses as discussed earlier. During (conversion) processes the energy of the overall system remains constant (first law of thermodynamics); but the energy loses its transformability according to the percentage of generated anergy (second law of thermodynamics). Portions of energy that are transformed into anergy accompanying an irreversible process are also called *exergy loss of irreversible processes.* The amount of generated anergy is proportional to the magnitude of *entropy*[29] of a system. (Baehr, et al., 2006). In this sense it is essential to transform the stored energy in a way that conserves as much exergy as possible and to avoid significant amounts of anergy.

The conversion of biomass into secondary energy can be realised in a physical-chemical way (i.e. gasification, pyrolysis, combustion or extraction of algae oil) on the one hand and in a biochemical way (i.e. fermentation of sugars into alcohol/ethanol and anaerobic digestion of biogenic substances into methane and carbon dioxide) on the other hand. Figure 12 gives a comprehensive overview of possible conversions paths concerning algae biomass (i.e. primary energy) into fuels of numerous kinds (i.e. secondary energy). *Methane (biogas)* and *hydrogen* are the two products which will be discussed in more detail in this paper. These products are the most promising and exergy conserving fuels for the generation of electricity based on algae. However, research in the USA has a strong focus on extraction of *algae oil* with a subsequent *biodiesel* production by transesterification. The conversion paths and products related with electricity production are highlighted; the corresponding transformation technologies are marked with bold letters: *Anaerobic digestion*, *extraction and transesterification,* respectively, and *biophotolysis*. The following section is structured by the conversion products. The content is grouped by the output products.

[28] W. Thomson stated in 1851: „It is impossible, by means of inanimate material agency, to derive mechanical effect from any portion of matter by cooling it below the temperature of the coldest of the surrounding objects".

[29] "Entropy" as a measure of the lack of a system's energy to do useful work was defined by R. Clausius (1865) following the principle of irreversibility combined with the non-existence of a "perpetuum mobile".

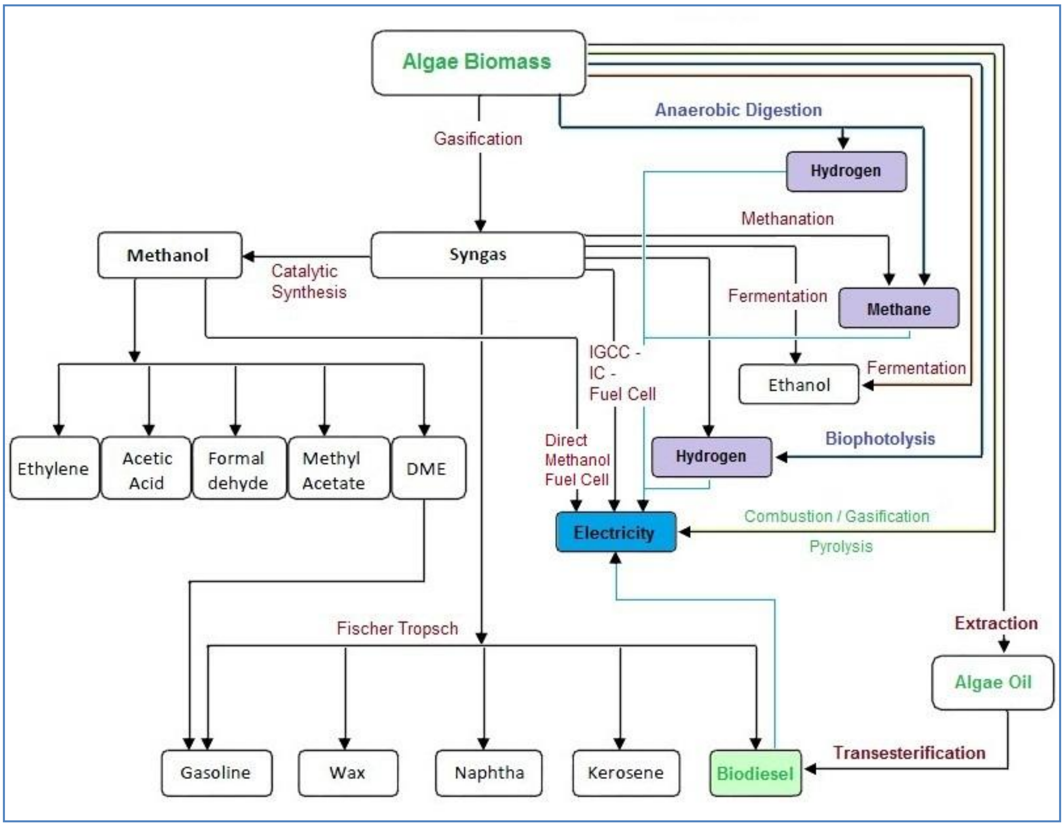


Figure 12: General conversion paths for algae biomass with focus on electricity (Oilgae.com, 2010), adapted

3.1.6.1 Biodiesel

Biodiesel as a fuel has its roots in Graz, Austria. The institute of Chemistry (IFC) of the Karl-Franzens-University in Graz The history of biodiesel reaches back to 1982 when first tests with RME (i.e. rapeseed methyl ester) were made. The first input sources for the production of biodiesel were rapeseed oil and used frying oil. In 1991, RME was produced in an industrial scale for the first time; in the same year RME was standardised by OE-NORM[30] (ÖNORM C1190). Used frying oil was introduced as an input source in an industry scale production in 1992; in 1994 the FME fuel (i.e. fatty acid methyl ester) was specified. Finally, EU standard for biodiesel was defined in 2009 (EN14214). Biodiesel can be blended with fossil petroleum diesel at different rates, for instance, as “B7” for a blend containing 7% of biodiesel. Due to regulations B7 has to be sold instead of pure diesel in Austria.

30 OE-NORM is a set of standards provided by the Austrian Standards Institute (http://www.as-institute.at).

Therefore, biodiesel covers 7% of Austria's diesel fuel demand at the moment (Mittelbach, 2009).

3.1.6.1.1 Biomass Input

Regarding algae biomass as a source for biodiesel production the input substrate is algae oil; the crude bio oil is separated from the concentrated algae mass by extraction processes (see 3.1.3.3.7). Algae residues (i.e. the press cake) can be used in various ways, for instance, as feed material used in aquacultures or as an input substrate for methane production.

3.1.6.1.2 Conversion Technology

The conversion of vegetable oil into biodiesel is based on the chemical manipulation of unsaturated fatty acids (i.e. the triglycerides) which are part of the bio oil. From a chemical point of view the transformation can be characterised as reaction of a fat or oil with an alcohol at the presence of a catalyst. The reaction (i.e. the transesterification) produces a mixture of methyl esters (i.e. biodiesel) and glycerol[31] as a by-product of high value. Figure 13 shows the conversion process.

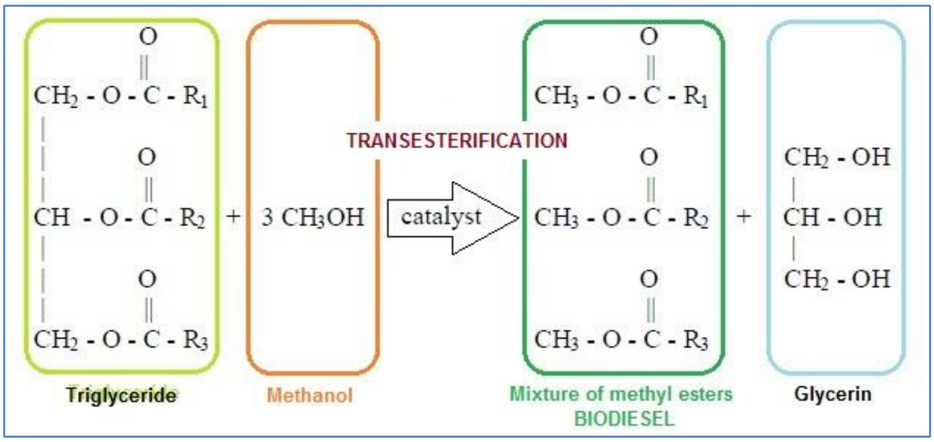


Figure 13: Production of biodiesel – transesterification process
(Van Gerpen, 2010), adapted

In production plants the transesterification process uses alkaline catalysts. However, enzymes may be interesting alternatives in the future (Van Gerpen, 2010). Figure 14 depicts the process flow of biodiesel production schematically.

[31] Glycerol derives from the Greek *glykýs*: sweet and from the Latin *cera*: wax. "Glycerol is a viscous, water-soluble, odourless, hygroscopic, sweet tasting and non toxic liquid" (Mittelbach, 2009).

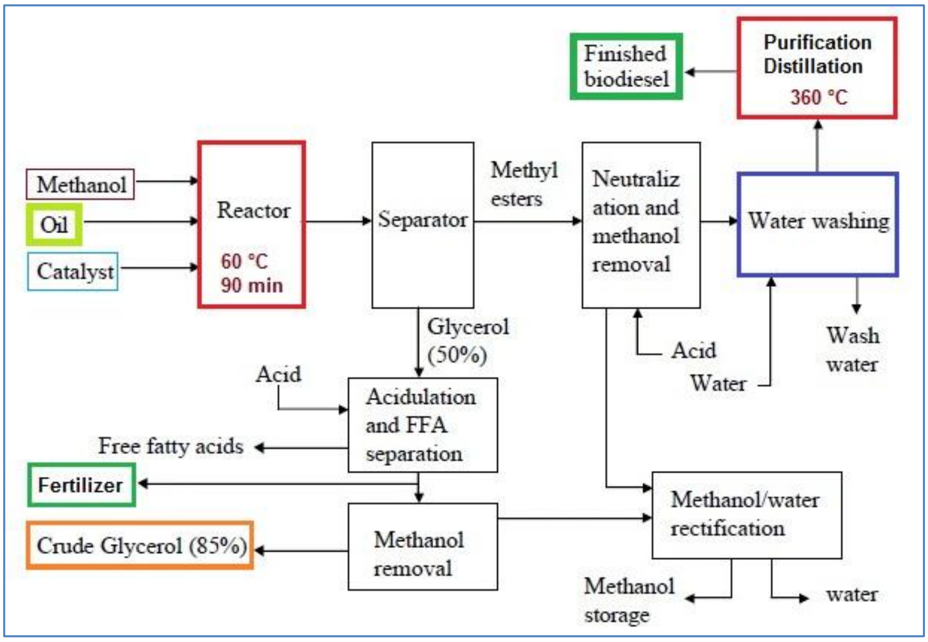


Figure 14: Schematic process flow of biodiesel production
(Van Gerpen, 2010), adapted

Oil and algae oil, respectively, is mixed up with an alcohol (i.e. methanol) and a catalyst in a reactor. The reactor temperature is 60 °C in order to optimise the transesterification process. Subsequently glycerol is separated from the mixture of methyl esters and is transmitted to a post production process. In this part of the plant glycerol is concentrated depending on its later use. Glycerol is used as base material for personal care products, for foods, for the production of urethanes and for the pharmaceutical industry. The glycerol treatment stage also produces substances which can be used as agricultural fertiliser. The separated methyl esters are transferred to cleaning stages; catalyst substances and methanol are filtered out by sedimentation and water washing steps. Finally, the cleaned methyl esters are distilled at high temperatures. By that the chemical properties of the final product can be adjusted (Van Gerpen, 2010), (Mittelbach, 2009).

3.1.6.1.3 Product Description

Biodiesel as a fuel is very close to petroleum diesel. The following table shows a comparison of characteristic parameters concerning biodiesel from algae oil and fossil diesel.

Table 12: Comparison of biodiesel and petroleum diesel
(Oilgae.com, 2010), (Mittelbach, 2009)

Parameter	Biodiesel from algae [EN 14214]	Petroleum diesel [EN 590]
Density at 15 °C [kg/m³]	860 – 900	820 – 845
Viscosity at 40 °C [mm²/s]	3.5 – 5.0	2.00 – 4.50
CFPP[32] [°C]	5 – -20	5 – -20
Cetane Number	≥ 51	≥ 51
Specific Energy Density [MJ/kg]	37.80	48.10
Biodegradability after 21 days	> 99%	72%

3.1.6.1.4 Comparison with Crude vegetable oil

Of course, vegetable oils have the potential be used directly as fuel. The advantages are *direct utilisation*, there is *no glycerol production* and *no energy consuming chemical processes* are needed. However, there are significant disadvantages such as a low viscosity of the fuel compared to biodiesel in general and especially at temperatures below 40 °C. As a matter of fact the fuel does not meet common engine specifications and the fuel has to be pre heated prior to the combustion in an engine (Mittelbach, 2009).

3.1.6.1.5 Evaluation of Biodiesel

The overall energy balance of biodiesel production is positive which means that the energy efforts that are necessary for the production processes are significantly lower than the energy content of the final product. The energy balance (i.e. the input-output relationship) for RME is positive and varies between 1:1.88 and 1:5.51 depending on feedstock. This means that the overall input of energy including growing and harvesting efforts as well as process energy efforts for the biodiesel production is considerably lower than the energy contained in the final product. Furthermore, the positive balance is accompanied by the output of useful by-products. Compared to petroleum diesel biodiesel saves approximately 2.3 – 3.2 kg CO_2 equivalents; biodiesel is 80 – 90% less toxic for algae etc. Nevertheless the production of biodiesel has some disadvantageous facets. On the one hand it is the demand for methanol which is commonly of fossil origin; on the other hand it is the need for process heat (i.e. for the reactor temperature and for the final distillation process) and water for the washing process filtering out catalyst substances. The water has to be treated before being released from the plant which once more

[32] CFPP: Cold filter plugging point.

consumes resources. In some American production plants the water in the dry washing stage is replaced by clay; however, the contaminated material subsequently is landfilled. Overall, biodiesel is a biofuels with a positive energy balance and can be used purely or blended with petroleum diesels. Low percentage blends are able to fuel common diesel engines without any modifications. Compared to crude vegetable oil biodiesel shows stable fuel parameters, very good exhaust gas values and is storable. The most important field of application is the transport sector. The following table shows a typical balance sheet concerning input and output materials and energy amounts, respectively. The data is taken from Kaltschmitt (Kaltschmitt, M. et al. [Hrsg.], 2009).

Table 13: Biodiesel production – balance sheet for materials and energy (Kaltschmitt, M. et al. [Hrsg.], 2009)
Legend: shaded table cells show energy and material inputs

Product balance sheet	Production materials (consumption)
Rapeseed oil: **1,000 kg**	Process steam: **415 kg**
	Cooling water (Δ t 10 °C): **25 m³**
Biodiesel: ***1,000 kg***	Electric energy: **12 kW h**
Glycerol (raw): ***128 kg***	Methanol: **96 kg**
Pharmaceutical glycerol: ***93 kg***	Catalyst material (natrium methylate 100%): **5 kg**
Industrial glycerol: ***5 kg***	Hydrochloric acid (37%): **10 kg**
	Sodium hydroxide (50%): **1.5 kg**
	Nitrogen: **1 m³**
	Process water: **20 kg**

3.1.6.2 Biogas (methane)

Biogas is the product of a *biochemical degradation* of biomass. It is built during the *anaerobic digestion* of biomass by *microorganisms*. In contrast to the aerobic decomposition which can be described as a biologic and direct combustion of biomass setting free heat, the anaerobic decomposition of biomass occurs in multiple steps and is a rather slow process. This is caused by the fact that the involved microorganisms consume only very small amounts of the energy stored in the biomass. Therefore, almost all of the stored energy is available in the high grade transformation products, namely alcohol and methane. The fermentation of alcohol is one form of anaerobic digestion. Alcohol production is limited by the fact that only sugars (i.e. starch and cellulose) can be used as input matter. On the contrary, the generation of methane may use proteins, lipids and carbohydrates as input materials and therefore has a significantly broader spectrum of usage. Only lignin resists the degradation by microorganisms. In nature methanogenesis can be observed at locations where missing oxygen does not allow aerobic degradation of biomass, for instance, at the bottom of lakes or in swamplands. Ruminant animals also produce methane; a cow exhausts 200 litres of methane every day. The produced *biogas is a mixture of methane* at a concentration of approximately 60%, *carbon dioxide* at a concentration of about 30% and small amounts of other gases. Methane producing bacteria have a very long history; they exist since times when no oxygen was present in the atmosphere and are called archaea (see 3.1.2.2). Research in the field of biogas has a long tradition, too. Beginning in the 18^{th} century methane has been subject of interest for numerous scientists. These activities finally lead to the generation of biogas within tanks in combination with waste water treatment in the 1920s by the German Imhoff; many German municipalities run their vehicle fleet on biogas. However, cheap fossil oil stopped these developments (Wellinger, et al., 1991).

3.1.6.2.1 Biomass Input

As mentioned in 3.1.6.2 the input materials for anaerobic biogas generation can be proteins, lipids and carbohydrates which are the main components of algae. Compared with many of the land based energy crops algae do not contain lignin; as a matter of fact the whole biomass can be digested. With respect to transformation efficiency the production of biogas from algae appears advantageous because the biomass input can be liquid or humid. This means that the energy consuming drying processes (3.1.3.3.6) can be omitted.

3.1.6.2.2 Conversion by Anaerobic Digestion

The anaerobic digestion (i.e. the biochemical conversion) of biomass is realised step by step exclusively by groups of microorganisms which live symbiotically within the substrate. The occurring series of steps depends on microorganisms working at different speeds; therefore the speed of the complete biogas production is defined by the slowest step. The main steps are *hydrolysis*, *acidogenesis*, *acetic acid formation* and *methanogenesis*; the involved groups of microorganisms are *anaerobic hydrolysis bacteria*, *acid formers*, *acetic acid formation bacteria* and finally *methane bacteria*. The following section describes the main steps. The data is taken from Wellinger (Wellinger, 2009), (Wellinger, et al., 1991) and Kaltschmitt (Kaltschmitt, M. et al. [Hrsg.], 2009).

During the first step, *hydrolysis*, the biomass consisting of complex and polymeric organic materials is broken into a series of monomers by hydrolytic or fermentative bacteria. Proteins are degraded to amino acids, fats to fatty acids, glycerol and triglycerides; complex carbohydrates such as starch are converted to simple sugars, for instance, glucose. Hydrolysis is enabled through enzymes excreted by the bacteria; the enzymes act as catalysts. The composition of the generated products depends on the partial pressure of hydrogen within the substance. Low hydrogen concentrations promote the generation of acetic acid; higher concentrations cause the generation of butanoic acid and lactic acid.

In the second stage, *acidogenesis*, acidogenic bacteria transforms the intermediate products of stage one into simple organic compounds and small amounts of carbon dioxide and hydrogen. These compounds are mainly short chain acids (i.e. propionic, formic, lactic, butyric, succinic acids), ketones (i.e. glycerol, acetone) and alcohols (ethanol, methanol).

The third step, *acetogenesis*, is another acid forming step. Some definitions of anaerobic digestion combine acidogenesis and acetogenesis to one acid forming step. In this step carbohydrate fermentation in combination with other metabolic processes are the important reactions. The most important output product is acetate forming a mixture of acetate, CO_2 and H_2. From a thermodynamic point of view the third step is very difficult because it depends on very low concentrations of hydrogen; otherwise the reaction would be endothermic, this means it would consume energy. The presence of hydrogen scavenging bacteria is necessary. In other words the existence of hydrogen during step three indicates that the digestion is inhibited.

The fourth step, *methanogenesis or methane fermentation*, finalises the biogas production. Methanogenic bacteria convert the soluble material into methane. 60% of the built methane come from the conversion of acetate into methane and carbon dioxide, 30% are generated by the reduction of carbon dioxide with hydrogen:

$$60\% \ldots Acetate \rightarrow CH_4 + CO_2$$

$$30\% \ldots CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

Methane fermentation defines the production rate because of the slow growth rate of methanogens compared to the acidogens. When anaerobic digestion is used in wastewater treatment systems or for the degradation of organic wastes hydrolysis can be rate-controlling. This is the case if the input material contains cellulose which takes longer time to be hydrolysed. In the case of algae the first step is not problematic. All four steps occur simultaneously within one substrate making use of synergetic effects between the actors and products of the single steps. Figure 15 depicts the four stages.

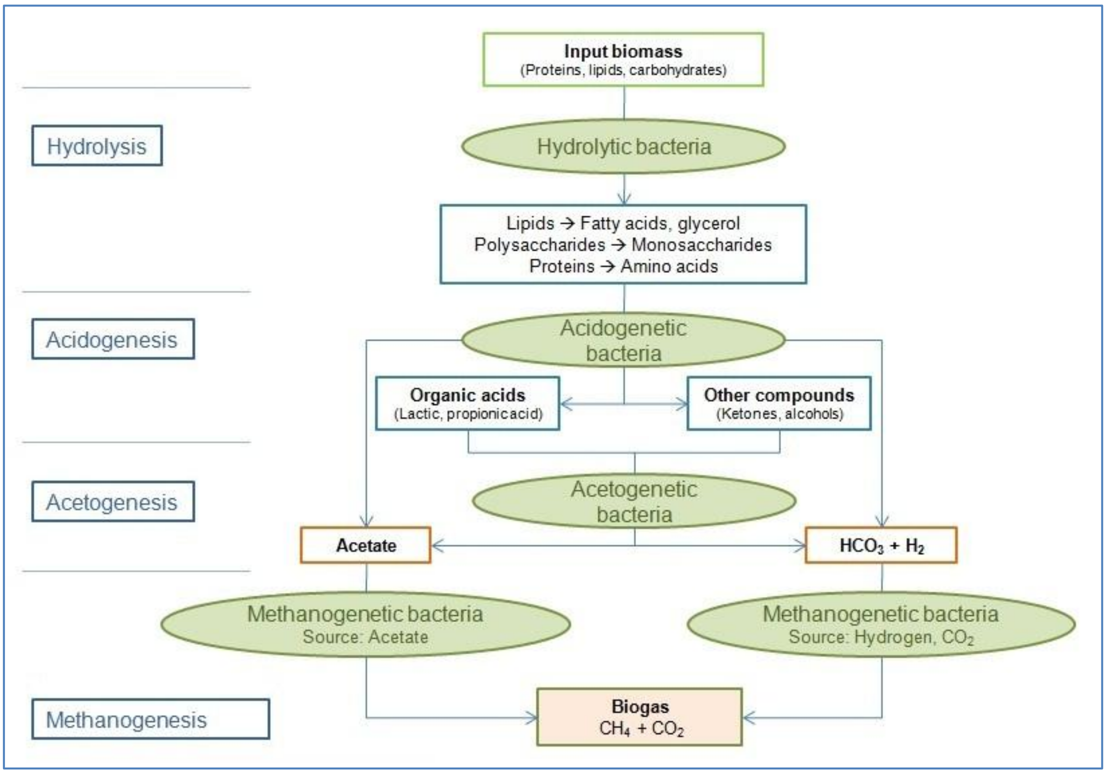


Figure 15: Anaerobic digestion of biomass to biogas (schema)
(Kaltschmitt, M. et al. [Hrsg.], 2009), (Wellinger, 2009), adapted

3.1.6.2.3 Product Description

The chemical composition of the generated biogas depends on different factors such as digestion temperature and duration. Nevertheless, the concentration of methane and carbon dioxide can be estimated based on the chemical structure of the input material. W.C. Boyle developed a formula for the chemical composition of the generated biogas with respect to the input material fractions (i.e. carbon, hydrogen, oxygen, nitrogen and sulphur) (Wellinger, et al., 1991):

$$C_aH_bO_cN_dS_e + (4a - b - 2c + 3d2e)H_2O =$$
$$= \frac{1}{8}(4a + b - 2c - 3d - 2e)CH_4 + \frac{1}{8}(4a — b + 2c + 3d + 2e)CO_2$$
$$+ dNH_3 + eH_2S$$

The following table shows typical biogas compositions for some characteristic classes of input materials. It can be seen that lipids produce a very high methane fraction whereas proteins also build some gaseous co-products; carbohydrates are degraded to methane and carbon dioxide in equal parts.

Table 14: Biogas compositions for different base materials
(Wellinger, et al., 1991)

Base material	CH_4	CO_2	NH_3	H_2S
Carbohydrates (Glucose)	50%	50%	-	-
Lipids	71%	29%	-	-
Proteins	38%	38%	18%	6%

During anaerobic digestion approximately 7% of the energy contained in the input biomass is consumed by the growth of the microorganisms. This means that as much as 90% of the energy is conserved in the form of methane. As a matter of fact the fermentation process does not produce recognisable amounts of waste heat.

3.1.6.2.4 Process Parameters

The methane concentration of the biogas can be influenced within certain limits. The following parameters can enhance the contained methane.

Table 15: Digestion parameters effecting the methane concentration
(Kaltschmitt, M. et al. [Hrsg.], 2009), (Wellinger, et al., 1991), adapted

Parameter	Effect
Input material	Input biomass with high lipid contents and low oxygen contents produces more methane than carbohydrates and proteins; in addition, methane production is higher if the base material does not contain lignin structures.
Input interval	In order to avoid unwanted temperature changes within the fermenter an automatic and quasi continuous input of biomass substrate is optimal; this matches perfectly with a continuous harvesting process of algae biomass.
Water content of substrate	High water contents of the input source are able to bind carbon dioxide; therefore the methane fraction within the gas is higher.
Temperature of substrate	High process temperatures effect higher CO_2 concentrations and a lower methane fraction within the gas.
Ambient pressure within the digester	High ambient pressure enhances the CO_2 solubility of the substrate; as a matter of fact the methane fraction within the gas rises.
Digester retention time	The longer the substrate is in the digester the higher are methane yields; especially after the completion of the CO_2 emitting hydrolysis methane concentrations in the biogas may rise.
Pre-digestion of input material	Digestion processes can be optimised if the input material is homogeneous and inoculated with bacteria.
Preparation of input substrate	Digestion processes can be accelerated by using chopped input substrates.

It gets evident that the usage of microalgae as an input substrate for biogas generation is highly advantageous. Harvested algae paste fulfils most of the prerequisites for an optimal digestion: the substrate is homogenous and smooth which means that chopping procedures may be omitted; it contains fats, lipids and carbohydrates but no lignin structures. In addition the whole algae biomass can be utilised without losses compared to other input sources.

3.1.6.2.5 Evaluation of Biogas

Roughly, biogas is a gaseous mixture of methane (CH_4, 66%), carbon dioxide (CO_2, 33%) and small fractions of various other gases. The *net calorific value of biogas is 21.5 MJ/m³*. During combustion of 1 m³ of biogas with a methane content of 60% 5.71 m³ of air are needed. Biogas may contain some unwanted components. Table 16 gives an overview of common biogas components. The data is taken from Kaltschmitt (Kaltschmitt, M. et al. [Hrsg.], 2009). Especially hydrogen sulphide can be problematic due to its corrosive nature.

Table 16: Components and net calorific value of biogas
(Kaltschmitt, M. et al. [Hrsg.], 2009)

Component	**Concentration** [% of volume]
Methane (CH_4)	45 – 75
Carbon dioxide (CO_2)	25 – 55
Water (H_2O)	2 (@20 °C) – 7 (@ 40 °C)
Hydrogen sulphide (H_2S)	0 – 2
Nitrogen (N_2)	< 5
Oxygen (O_2)	< 3
Hydrogen (H_2)	< 1
Characteristics	**Value**
Net calorific value	21.5 MJ/m³

Biogas can be used as a universal energy source. It can deliver electric energy, heat or be utilised as fuel for mobility purposes. Biogas can be utilised in industrial scale combustion plants delivering heat. It can be used in combustion engines (i.e. for stationary and mobile applications) for the production of electric energy. Another option is the usage as fuel for CHP plants[33]. The plants may implement gas

[33] CHP stands for combined heat and power systems. These systems use fuel dually. In the first stage engines are run to produce electric energy. The waste heat is recovered and used in the form of process heat or in for district heat systems. This way the total efficiency of the usage of fuel can be optimised.

powered Otto-engines, micro gas turbines (i.e. for electric power outputs in the range of 30 to 100 kW_{el}) or gas turbines. Furthermore, biogas can be used as car fuel in cars designed for CNG (i.e. compressed natural gas); after some cleaning stages biogas can also be fed into gas grids (Kaltschmitt, M. et al. [Hrsg.], 2009).

3.1.6.3 Hydrogen [H_2]

Hydrogen is a very advantageous energy carrier due to its energy density which is significantly higher than the energy density of gasoline and due to the fact that it does not contain carbon. Therefore its combustion will not emit greenhouse gases. Hydrogen is also capable of being utilised via high efficient fuel cells at low temperatures. This means that the stored chemical energy is transformed into electric energy by a galvanic cell. Nevertheless, the production of hydrogen is very expensive; furthermore, the storage of pure hydrogen bears many obstacles because the substance has a very low density (even when stored in liquid form) and is highly volatile. Currently, the hydrogen is mainly produced by steam reforming of natural gas which is not sustainable. Renewable ways of isolating hydrogen aim to make use of hydrogen generation processes which can be observed in natural processes (i.e. photosynthesis and digestion); alternatively, electrolysis (i.e. water splitting: $H_2O \xrightarrow{energy} H_2 + O_2$) may be powered by renewable energy sources. Finally, organic waste materials may be decomposed thermo-chemically to obtain hydrogen. According to NREL (i.e. U.S: national renewable energy laboratory) the following methods concerning a renewable hydrogen production are under research (NREL.gov, 2009): *Fermentation*, *biological water splitting (biophotolysis)*, *photo-electrochemical water splitting*, *conversion of biomass and wastes*, *solar thermal water splitting* and *renewable electrolysis*. This paper only discusses methods which are directly related to biochemical processes, namely the production of pure hydrogen as an application of anaerobic digestion processes and photosynthetic processes, respectively. Figure 16 shows these production paths in context with other methods.

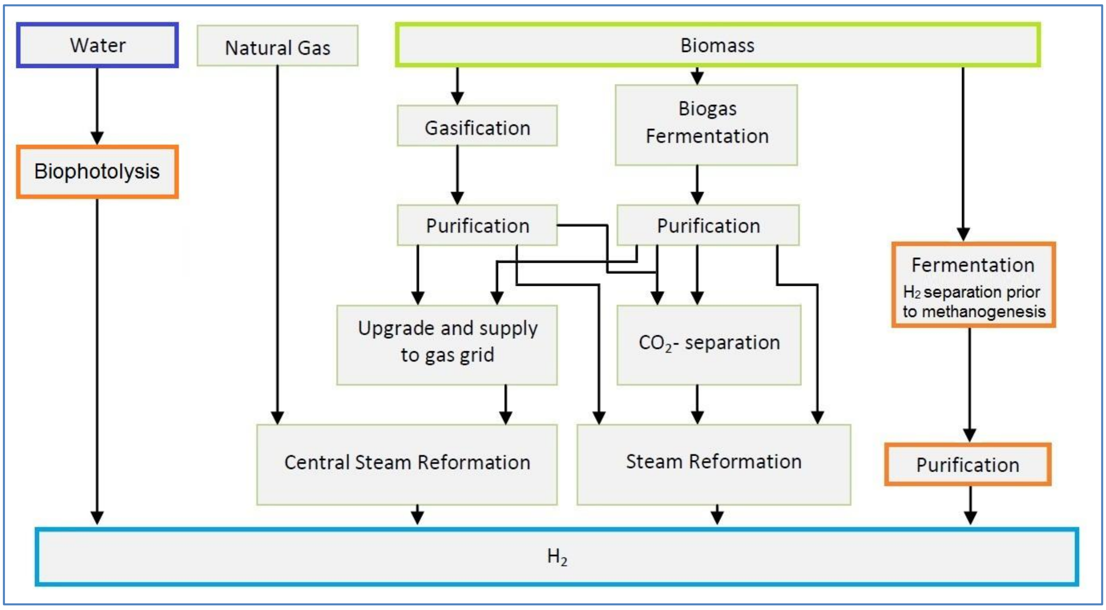


Figure 16: Hydrogen production paths – overview
(Oilgae.com, 2010), adapted

3.1.6.3.1 Biomass Input

The input materials for the hydrogen generation via anaerobic digestion may be the same as for biogas production. Algae have ideal characteristics with respect to digestion (see 3.1.6.2.5).

3.1.6.3.2 Fermentative Hydrogen Production

Fermentative hydrogen production uses anaerobic digestion processes. As described above (see 3.1.6.2.2) during acid forming stages (i.e. acidogenic and acetogenic steps) of digestion it is crucial to keep the partial pressure of hydrogen very low. Normally, methane bacteria consume the built hydrogen in order to produce methane. According to the information given in section 3.1.6.2.2 an amount of about 30% of the generated biogas is generated by the reduction of carbon dioxide with hydrogen:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

One of the reactions forming of molecular hydrogen out of sugar (i.e. $C_6H_{12}O_6$) is:

$$C_6H_{12}O_6 + 2H_2O \rightarrow 2CH_3COOH + 2CO_2 + 4H_2$$

This means that one sugar molecule can release 4 hydrogen molecules. According to research at Princeton University these yields are the ideal yields; actual experiments have resulted to lower yields. Possible reasons for lower yields are intracellular processes which recycle the generated hydrogen (Princeton University, 2004). However, research is in progress to isolate the hydrogen at the described stages in order to harvest pure bio generated hydrogen prior to the methanogenesis. Research by NREL tries to optimise hydrogen yields of fermentation. In the annual project progress report for the fiscal year 2007 the authors published achievements as followed (NREL.gov, 2008):

Table 17: NREL research results – H_2 from fermentation, 2008

Characteristics	Units	Theoretic maximum	Biologic maximum	2013 Target	2007 Status
Yield of H_2 from glucose	Mole H_2 per mole glucose	12	4	4	2.1
Feedstock cost	$ cents per lb glucose			10	13.5 (as of 2003)

The annual report for the fiscal year 2005 looked very similar (NREL.gov, 2006):

Table 18: NREL research results – H_2 from fermentation, 2006

Characteristics	Units	Theoretic maximum	Biologic maximum	2010 Target	2005 Status
Yield of H_2 from glucose	Mole H_2 per mole glucose	12	4	4	2.1
Feedstock cost	$ cents per lb glucose			10	13.5 (as of 2003)

Comparing the results makes evident that it is difficult to reach even the yields which are limited by biologic pathways: The current status of 2005 didn't change during the next two years of research; the yield could not be enhanced. The same impression applies to the feedstock costs.

3.1.6.3.3 Biophotolysis of Water by Algae

In analogy to the fermentative hydrogen production biophotolysis makes use of hydrogen generation processes which occur naturally. Whereas the former concentrates on hydrogen which is built during anaerobic digestion the latter focuses on photosynthetic hydrogen production (see 3.1.2.3.1.2). There are some research activities experimenting with algae which are, for instance, kept under anaerobic and dark conditions before being brought back to light; in situations like this the algae species *scenedesmus* produces molecular hydrogen. Another example is a hydrogen producing, genetically manipulated algae species (a *chlamydomonas mutant*) which was able to organise hydrogen production as well as carbon fixation within a single photo system (FAO - Food and Agriculture Organization of the United Nations , 1997).

3.1.6.3.4 Combined Methods

In this constellation anaerobic bacteria are combined with photosynthetic bacteria. Theoretically, it is possible to obtain 12 moles of hydrogen out of one mole of glucose. Anaerobic bacteria would generate organic acids out of sugar which is part of a variety of input sources such as biomass or biowaste. Photosynthetic bacteria subsequently would capture light energy to complete the hydrogen generation which is energy consuming (see "acetogenesis" in 3.1.6.2.2).

3.1.6.3.5 Evaluation of hydrogen

Hydrogen has a high potential as a broadly used future energy carrier. There are many theoretically possible ways of hydrogen purification and generation, respectively. In general, there are two main types of sustainable hydrogen generation. Firstly, it is hydrogen from organic (i.e. primary) sources:

$$organic\ source + energy \ \rightarrow hydrogen + CO_2$$

Primary sources can biomass or waste in general and sugar in particular; corresponding generation methods separate hydrogen from organic structures setting free CO_2. Secondly, it is hydrogen from water splitting:

$$energy\ from\ secondary\ source + water = hydrogen + oxygen$$

In this case renewable energy is used to split water into hydrogen and oxygen; this can take place within organic structures in biochemical processes or technically with the use of, for instance, solar energy (Princeton University, 2004). Currently, industrial hydrogen production mainly relies on the first method by using steam reformation of biogas or natural gas and gasification of organic substances. Water splitting technologies (i.e. electrolysis) which are powered by different renewable sources and biophotolysis of water are sustainable hydrogen generation alternatives; especially the latter method is strongly related to natural processes (i.e. photosynthesis) which produce hydrogen as an intracellular energy carrier. Apart from the fact that large scale hydrogen production on a sustainable base needs long term research and development to become economically feasible reality it has to be considered that there is the challenge of hydrogen storage and transport which has to be accepted.

3.1.6.4 Ethanol, Syngas and Others

As depicted in section 3.1.6 (Figure 12) there are several other ways of transforming biomass into secondary energy carriers and fuels, respectively. There is a group of physical-chemical conversions such as *pyrolysis* and *gasification*[34]. These conversion processes are used to transform biomass into (energetically or chemically) useful components by exposing it to certain atmospheric and thermal conditions. The generated products are mainly gaseous: methanol, syngas, etc. In further chemical conversions liquid fuels and high value chemicals can be synthesised on the base of the gases. Table 19 gives an overview of the most important thermo-chemical conversion types.

Table 19: Thermo-chemical conversion types
(Kaltschmitt, M. et al. [Hrsg.], 2009), simplified

Process	Thermo-chemical conversion	Oxygen supply	Temperature	Products
Combustion	Heat up and drying, pyrolytic decomposition, gasification, oxidation	$\lambda \geq 1$	800 – 1,300	Hot flue gas
Gasification	Heat up and drying, pyrolytic decomposition, gasification	$0 < \lambda < 1$	700 – 900	Combustible gas
Pyrolysis	Heat up and drying, pyrolytic degradation	$\lambda = 0$	450 – 600	Combustible gas

Sugars, on the other hand, can be converted biochemically by using *fermentation*. The main product hereof is ethanol (i.e. alcohol).
These methods are not discussed in more detail in this paper because they focus more on wooden input materials than on algae biomass.

3.1.7 Production of Electricity

As stated in the introduction of this master thesis, compared to the total final energy consumption the consumption of electricity has been increasing disproportionately over the last decades; furthermore, it is expected to further increase globally for the next centuries. Electricity will become the most important form of secondary energy:

[34] Pyrolysis and gasification are thermo-chemical transformations of organic matter; they are characterized by different temperatures and distinct concentrations of oxygen within the conversion process. Pyrolysis occurs at temperatures between 200 and 600 °C under absence of oxygen (λ=0). Gasification needs higher temperatures of about 400 to 700 °C; there is some oxygen, but not enough for a complete combustion ($0 < \lambda < 1$). The λ-value defines the oxygen supply during the process. The amount of oxygen which is needed to oxidise all of the organic substances corresponds to a λ-value of 1. If there is less oxygen than needed the λ-value is between 0 (no oxygen) and 1. $\lambda = m_{air, total}/m_{air, min}$.

on the one hand the distribution infrastructures are very well developed; on the other hand electricity can be transported easily and it can be used universally for almost any kinds of applications. The upcoming development of electric mobility pays its tribute to this development. The use of electricity distributed via meshed grids has significant advantages: The distribution of energy is standardised; the grid allows decentralised outtake and input of energy. In addition, the consumption of electricity does not emit exhaust gases at the location of consumption by the final customer. As a matter of fact this paper discusses the conversion of algae based energy into electric energy taking algae based biogas as an example; in addition, it puts a side glance on hydrogen and biodiesel as a source for electricity generation.

3.1.7.1 Biogas to Electricity

The most efficient way to produce electricity from biogas can be realised via a combined heat and power plant. In a plant like that biogas is combusted in industrial size *gas engines* which are rather huge derivates of common Otto engines. Alternatively, so called *pilot injection gas engines* can be used. The engines are connected with electric generators. The output of the generators is alternating current matching the frequency of the connected grid. Due to better manageability and scalability parameters synchronous generators[35] are preferred to asynchronous generator types. Table 20 outlines the characteristics of the named gas engines. The data is taken from Kaltschmitt (Kaltschmitt, M. et al. [Hrsg.], 2009).

Table 20: Characteristics of gas engines
(Kaltschmitt, M. et al. [Hrsg.], 2009)

Characteristics	Otto engine	Pilot injection
Ignition type	Extraneous ignition	Self-ignition
Ignition fuel	-	Diesel (> 5% of nominal power)
Electric Power	20 – 30,000 W	5 – 300 W
Electric efficiency	Up to 42%	Up to 40%
Economic life time	> 60,000 h	n. a.
Own needs (percent of nominal power)	Up to 3%	Up to 3%

In addition, the engines produce heat which can be used in district heat systems or for process heat needs. Utilising the produced heat increases the overall efficiency

[35] Synchronous generators are directly connected to the alternating current grid. This means that the rotation speed of the generator is fixed to match with the frequency of the electric grid.

significantly. The heat is collected by heat exchangers within the cooling water and oil cycles and from the exhaust gases, respectively. The output temperature of the heat exchangers is about 100 °C; the backflow temperature may vary between 55 and 70 °C. A certain amount, approximately 10 to 30%, of heat energy is needed for the heating system of the biogas fermenters. Another portion of the waste heat may be used for the heating system of the algae growing ponds. This type of usage also applies to the waste gas of the engines: because algae need CO_2 for optimal growth the exhaust gases can be bubbled into the algae pond. As a positive effect, the CO_2 cycle of the whole system can be short circuited locally; significant portions of the green gases within the flue gases can be recycled directly into the algae growing process (Kaltschmitt, M. et al. [Hrsg.], 2009).

3.1.7.2 Hydrogen to Electricity

As mentioned above (see 3.1.6.3), hydrogen is an energy carrier which does not contain carbon. As a matter of fact its usage does not emit greenhouse gases. Depending on the desired energy output hydrogen can be utilised in different ways. Hydrogen can be combusted or used in fuel cells.

3.1.7.2.1 Combustion

The combustion of hydrogen works similar to the combustion of biogas in conventional Otto engines. This way hydrogen can be used for mobility applications, for instance, in cars or busses as a low emission fuel. In addition, the engines can also power electric generators. The difference to biogas and fossil fuels is that in the case of hydrogen combustion the exhaust gases do not contain any carbon dioxide. However, efficiencies of combustion engines are not very high (i.e. approximately between 25 and 36% for Otto engines). If the energy that is needed to produce hydrogen from primary resources is taken into consideration the total efficiency of such a system is rather low.

3.1.7.2.2 Fuel Cell

Fuel cells are a more direct way of producing electricity from hydrogen. Fuel cells are galvanic devices which are fed with hydrogen and oxygen from ambient air. The output of a fuel cell is direct current on the one hand and water combined with some waste heat on the other hand. Most types of fuel cells are characterised by the reaction of hydrogen with oxygen to water. Figure 17 shows schematic view of a hydrogen powered fuel cell.

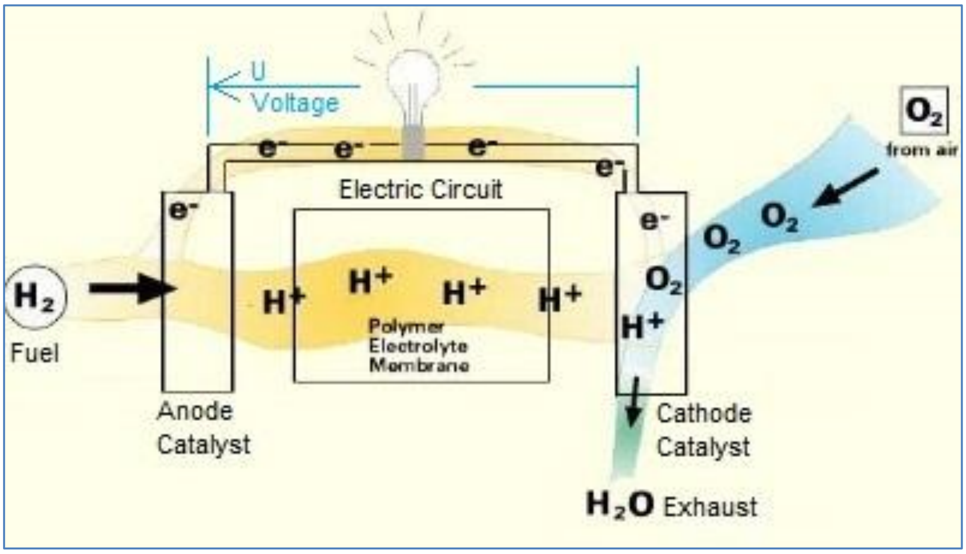


Figure 17: Hydrogen powered fuel cell: schema
(FuelCells.org, 2010)

From its principle a fuel cell works like battery. It consists of two electrodes (i.e. the electrically positive anode and the negative cathode) which are surrounded by an electrolyte. Hydrogen is fed into the system via the anode. A catalyst triggers a splitting process which divides the hydrogen atom into a proton (H^+) and an electron (e^-). The protons walk through the electrolyte to the cathode; the electrons are hindered to do so; instead the electrons find their way to the cathode via an external path. At the cathode, the hydrogen protons react with oxygen and the electrons to water (H_2O). As a result a voltage (i.e. a difference in electrical charge, the so called cell voltage) is built up between the electrodes. That way the fuel cell is able to deliver electricity. The reaction equation of a fuel cell is rather simple:

$$2H_2 + O_2 \rightarrow 2H_2O$$

The main difference between the variants of fuel cells is defined by properties of the electrolyte and by the temperature of operation.

Because of the fact that in current scenarios hydrogen has to be generated out of primary energy carriers such as natural gas the efficiency of fuel cells is evaluated as the efficiency of fuel cell systems which also include the energy efforts to generate hydrogen. According to Baehr et al. *the total efficiency of a hydrogen powered fuel cell system based on fossil resources is about 40%*. This means that less than half of the input of primary energy is converted into electricity (Baehr, et al., 2006). It has to be considered that fuel cell applications are at development stage at the moment. Thus the prices for fuel cells are very high and the technology is not available for industrial usage at the moment.

3.1.7.3 Biodiesel to Electricity

As an alternative to biogas and hydrogen also biodiesel can be used to generate electricity. Diesel engines have efficiencies of between 43% and about 50% for very large, slow rotating and turbo charged engines. With respect to developments towards electric mobility biodiesel could be used to produce electricity in stationary applications instead of being distributed to the final customer and to the single mobility application (i.e. cars etc.), respectively.

3.1.7.4 Comparison of Methods and Annotations

Comparing the three alternatives, namely, electricity from biogas, from hydrogen and from biodiesel it has to be stated that the first method seems to have the most advantages. Biogas can be produced by the use of known processes from algae biomass utilising the whole biomass substrate. The combustion of biogas produces electricity, heat and CO_2. Both waste products can be reused to optimise algae growing and fermentation processes. The production of hydrogen as well as the usage of hydrogen for electricity production is an interesting alternative. However, there are some obstacles: the generation process as part of the fermentation is subject of research and not very well developed; in addition, only some portions of the biomass can be transformed into hydrogen. Storage of hydrogen is another difficult subject because of the very deep temperatures of minus 253 °C which are necessary to store hydrogen in a liquid phase. Finally, the fuel cell technology has to be further developed to be affordable. Nevertheless, researchers all over the world are putting big efforts into the field of hydrogen research and development. Biodiesel on the other hand can be used for mobile applications running common technology as well as for medium and large scale electricity generation. With respect to algae it has to be stated that there is the disadvantage that only the oil content of the biomass can be utilised.

3.2 Mass Flow and Energy Balance

This section concentrates on electricity generation from algae biogas. It should give a feeling concerning the needed land area for the production of electric energy in a plant of the size of one mega watt. The magnitudes will be compared to the corresponding values of a comparable production capacity based on biogas from maize silage.

3.2.1 Production Capacities and Agricultural Areas

For the evaluation of an energy crop with respect to its production capacities the following numbers are characteristic: on the one hand it is the energy density of the crop per hectare and year (i.e. the achievable GJ/ha/a), on the other hand it is the land area required to produce a certain amount of energy. As a reference a desired output of one megawatts of electric energy is taken into consideration.

As described in 3.1.4.2 algae show an average growth of at least $20\ g/m^2/day$. According to Pierpaolo Cazzola, John R. Benemann and Oilgae.com near term (i.e. this means about five years) oil yields are expected to be around $30{,}000\ L/ha/year$ (Cazzola, 2009), (Benemann, 2009), (Oilgae.com, 2010). Assumed that the average oil content of algae is about 20% this amount corresponds to a biomass growth of approximately $150\ t/ha/year$. This value equals a biomass growth of $41\ g/m^2/day$. Combined with calorific values (see Table 10) for algae of $18 - 23\ \mathrm{GJ}/t$ the grown energy sums up to between $2{,}700\ GJ/ha/year$ and $3{,}450\ GJ/ha/year$.

As a reference, energy maize produces a yearly yield of about $55\ t/ha/year$ of fresh material when grown on average European soils (Lamp, 2008); the yielded fresh mass contains about 28% of dry matter (Ortner, 2010). With a calorific value of $16.5\ \mathrm{GJ}/t$ with respect to dry mass (see Table 11) the energy density is as high as $254\ GJ/ha/year$. This value corresponds to the following land area need for the growth of maize with the energy of one gigajoule within one year.

$$\mathrm{area_{maize}}/GJ = 10{,}000\ m^2/254\ \ GJ = 39.37\ m^2/GJ.$$

The calculations show that even with a low daily average growth of $20\ g/m^2/day$ the stored energy of algae ($1{,}500\ GJ/ha/year$) is six times higher than the energy stored in energy maize ($254\ GJ/ha/year$). As a matter of fact the needed surface area and land area, respectively, concerning algae culture systems is less than 20% compared to energy maize.

$$\mathrm{area_{algae}}/GJ = 10{,}000\ m^2/1{,}500\ \ GJ = 6.67\ m^2/GJ$$

Research will be able to increase the described ratio from six to twelve in the next years. Figure 18 outlines the described magnitudes with respect to land use for the production of energy crops delivering one gigajoule of energy per year comparing algae with energy maize at the current situation and in a prediction for the next five years (i.e. short term R&D increasing the daily growth of algae).

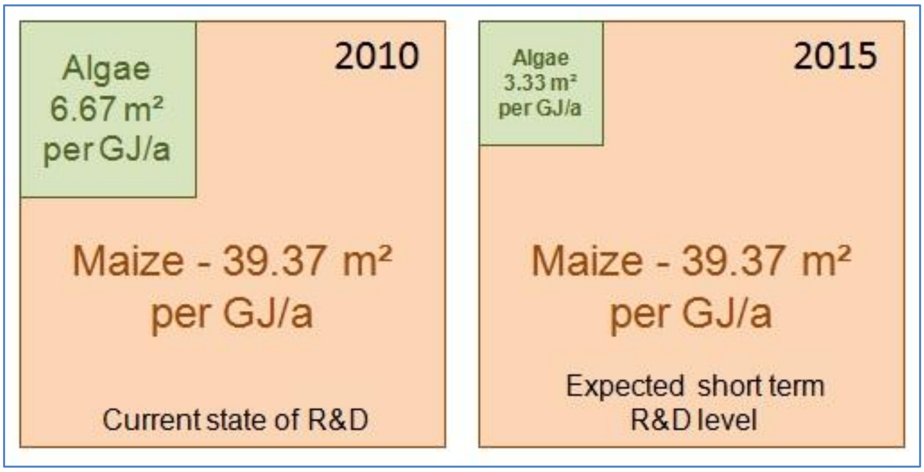


Figure 18: Comparison of land use – algae vs. maize

3.2.2 Theoretic Maximum of Algae Biomass Production

It is interesting to have a look at the theoretic maximum of algae biomass production because it gets easier to understand the potentials which were discussed in the previous section. In literature, different values for photosynthetic efficiency of algae are to be found. The most extreme values for PE are 2% (Barsanti, et al., 2006) and 9% (Zijffers, et al., 2010) (see 3.1.2.3.1.5). Higher plants show a PE of 1% (Hofbauer, 2009). The following calculations consider these boundaries; in addition they use data from the Photovoltaic Geographical Information System (PVGIS) as provided by the European Commission (EC Joint Research Centre, 2008).

Table 21: Calculation of maximum algae biomass growth

Eastern Austria				
Irradiation per year (PVGIS)	1,400			kW h/m²
Irradiation per day	3,836			W h/m²
PE	**1%**	**2%**	**9%**	
Biomass energy generation per day	38	77	345	W h/m²
HHV algae (Spirulina)	20			MJ/kg
Unit conversion	5,505			W h/kg
Calculated: biomass generation per day	**7**	**14**	**62**	**g/m²**
Southern Spain				
Irradiation per year (PVGIS)	2,100			kW h/m²
Irradiation per day	5,753			W h/m²
PE	**1%**	**2%**	**9%**	
Biomass generation per day		115	518	W h/m²
HHV algae (Spirulina)	20			MJ/kg

Unit conversion	5,505			W h/kg
Calculated: biomass generation per day	**10**	**21**	**93**	**g/m²**

3.2.3 Biogas Yields

In order to estimate achievable biogas yields from algae this paper takes maize as a reference crop and transfers the magnitudes to algal biomass sources by using algae core facts which are documented in literature.

3.2.3.1 Reference Energy Crop Maize

Beside Triticale, Barley and fodder beet maize is by far the best biomass gas producer at the moment (Wellinger, 2009). The following table shows the characteristics of maize. The data is taken from Mario Ortner (Ortner, 2010).

Table 22: Maize silage as biogas producer: characteristics and energy balance (Ortner, 2010)

Characteristics	Values
Energy crop	Maize milk-ripe
Yield	45 – 60 t/ha
Dry matter fraction (TS)	28%
Organic dry matter (oTS)	27.2%
Density	800 kg/m³
Biogas output based on oTS	568 m³ per tonne oTS
Biogas output based on fresh material	154 m³ per tonne fresh material
Energy balance	**Values**
Fresh material yield	45 – 60 t/ha
Organic dry matter fraction	27.2%
Organic dry material yield	12.2 – 16.3 t/ha
Net calorific value	16.5 GJ/t
Energy density of input material	202 – 269.2 GJ/ha
Biogas output	6,930 – 9,240 m³/ha
Energy density of biogas	148.995 – 198.66 GJ/ha
Ratio input energy – output energy	74%
Land area per GJ of biogas	37 – 50 m²/GJ biogas

The maize yield per hectare in combination with the biogas yield per tonne fresh material delivers a biogas yield between 6,930 and 9,240 m³ per hectare.

$$154\,\frac{m^3}{t} * 45\,\frac{t}{ha} = 6{,}930\,\frac{m^3}{ha}$$ ... Biogas output – low maize yield

$$154\,\frac{m^3}{t} * 60\,\frac{t}{ha} = 9{,}240\,\frac{m^3}{ha}$$ ... Biogas output – high maize yield

With a net calorific value of 21.5 MJ/m³ (see 3.1.6.2.5) the yearly produced biogas energy amounts to between 149 and 199 GJ/ha.

$$6{,}930\,\frac{m^3}{ha} *\ 21.5\,\frac{MJ}{m^3} = 149\ GJ/ha$$ ... Biogas energy density – low maize yield

$$9{,}240\,\frac{m^3}{ha} *\ 21.5\,\frac{MJ}{m^3} = 199\ GJ/ha$$ ... Biogas energy density – high maize yield

In comparison with the energy density of the input material of between 202 and 269 GJ/ha the output-input ratio is 74%.

$$45\,\frac{t}{ha} * 0.272 * 16.5\,\frac{GJ}{t} = 202\,\frac{GJ}{ha}$$ ... Input energy density – low maize yield

$$60\,\frac{t}{ha} * 0.272 * 16.5\,\frac{GJ}{t} = 269\,\frac{GJ}{ha}$$ ... Input energy density – high maize yield

$$\frac{149}{202} = \frac{199}{269} = 0.738$$ ... Output-input ratio, both cases

This means that in practical applications available in production scale *almost three quarters of the energy stored in maize can be transformed into biogas energy*.

3.2.3.2 Transfer Reference Data to Algae

Based on the magnitudes of energy production concerning maize as a reference the energy balance of algae can be assumed: With an annual algae yield of 73 tonnes (i.e. at an average and conservatively assumed biomass growth of $20\ g/m^2/day$) and an average net calorific value of 18 – 23 GJ/t the energy density of the algae biomass varies between 1,314 and 1,679 GJ/ha.

$$73\,\frac{t}{ha} * 18\,\frac{GJ}{t} = 1{,}314\,\frac{GJ}{ha}$$ ... Algae energy density – low H_u

$$73\,\frac{t}{ha} * 23\,\frac{GJ}{t} = 1{,}679\,\frac{GJ}{ha}$$ ... Algae energy density – high H_u

Supposed that the biogas production efficiency is as high as with maize, namely 74%, the energy density of the produced biogas is as high as between 969 and 1,238 GJ/ha which corresponds to a biogas production of more than 50,000 m³ per hectare.

$$1{,}314\,\frac{GJ}{ha} * 0.738 = 969\,\frac{GJ}{ha}$$ ... Biogas energy density – low H_u

$$1{,}679\,\frac{GJ}{ha} * 0.738 = 1{,}238\,\frac{GJ}{ha}$$ ... Biogas energy density – high H_u

$$1000 *\ (969\,\frac{MJ}{ha})/(21.5\,\frac{MJ}{m^3})\ = 45{,}088\ \frac{m^3}{ha}$$ ... Biogas output – low H_u

$$1000 *\ (1{,}238\,\frac{MJ}{ha})/(21.5\,\frac{MJ}{m^3})\ = 57{,}613\ \frac{m^3}{ha}$$ ... Biogas output – high H_u

This is at least five times the output of energy maize. Table 23 illustrates the assumptions.

Table 23: Assumed energy balance for algae as biogas producer

Energy balance algae – Assumptions	Values
Energy crop	Algae
Dry material yield	73 t/ha (@ a growth of 20 g/m²/day)
Net calorific value	18 – 23 GJ/t
Energy density of input material	1,314 – 1,679 GJ/ha
Ratio input energy – output energy	74%
Assumed output	
Energy density of biogas	969.4 – 1,238.7 GJ/ha
Biogas output	45,088 – 57,613 m³/ha
Land area per GJ biogas	8 – 10 m²/GJ biogas

The assumed figures concerning algae as biogas producer base on current and rather conservatively estimated algae growth rates. Taking into account that algae growth rates are expected to be multiplied within the next decades (see Table 6) the potential of algae as base material for biogas production appears rather impressive.

3.2.4 Fermentation Process Optimizations

Most algae substrates contain significantly more nitrogen than energy crops, for instance, maize (see 3.1.4.3, Table 9). If the nitrogen concentration of the fermentation substrate gets too high (i.e. about 6 – 10 g/L) ammoniac (NH_3) is formed; as a result the methanogenesis slows down. Ammoniac forming can be overcome by either adding gypsum to the fermentation substrate or by using grass biomass as a co-fermentation substrate. Biogas generation experience shows that the amount of gypsum which has to be added to optimize the fermentation process should be 6 – 10 kg gypsum per ton of ammonia (NH_4-N). This amounts to about 4 – 5% of the substrate input (Ortner, 2010).

3.2.5 Electricity Production

Following paragraph 3.1.7.1 (Biogas to Electricity), the produced biogas is converted into electric energy in a combined heat and power plant (CHP). Figure 19 shows an algae and biogas powered CHP plant schematically. It shows that about 39% of the energy delivered with the biogas is transformed into electricity. Beside approximately 17% of thermal losses (i.e. friction within engine, heat radiation of engine and heat of the exhaust gas) about an equal amount of heat energy (i.e. about 44%) is generated. Exhaust gases and heat can be utilised to optimise algae growing and fermentation. A small portion of the generated electricity (i.e.

approximately 3%) are needed by the plant itself. The data was provided by Dr. Ortner (Ortner, 2010).

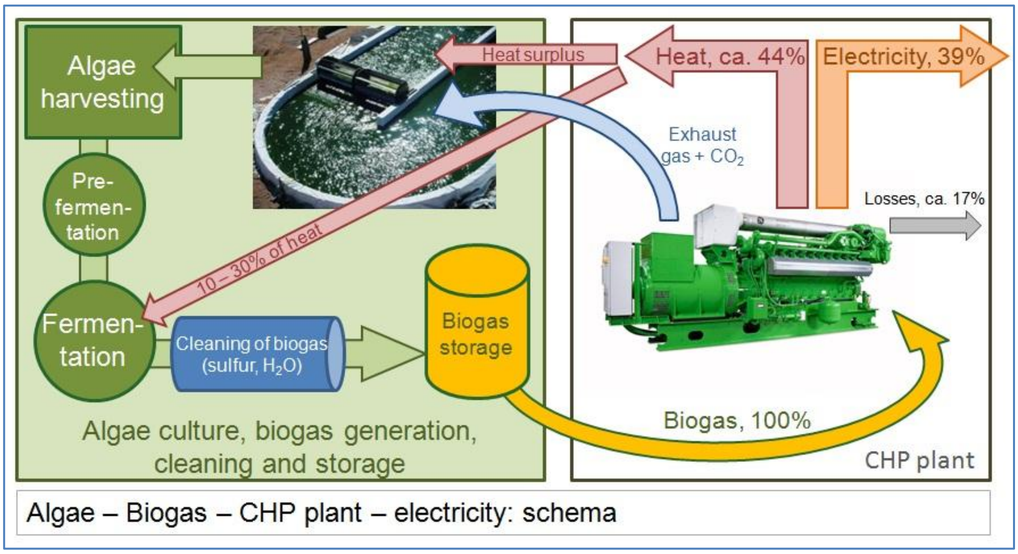


Figure 19: Schema of algae and biogas powered CHP plant

Based on the biogas yield assumptions in 3.2.3 the energy balance of the electricity production from biogas in a CHP plant with an electrical output of 1 MW is described in the following table.

Table 24: Energy balance electricity production from biogas (CHP) (Ortner, 2010), (Kaltschmitt, M. et al. [Hrsg.], 2009)

Energy balance electricity production	**Values**
Engine type	Otto cycle combustion engine
Electrical efficiency η_{el}	39%
Thermal efficiency η_{th}	44%
Losses	17%
Own consumption (electricity)	3%
Electrical power (set with 39%)	1,000 kW
Thermal power (calculated with 44%)	1,128 kW
Losses (calculated with 17%)	436 kW
Output (theoretical)	**Values**
Electrical output per hour	1,000 kW h
Thermal output per hour	1,128 kW h
Electrical output per year (@8,500 flh)	8,500,000 kW h
Thermal output per year (@8,500 flh)	9,588,000 kW h
Input	**Values**
Biogas energy input per hour	2,564 kW h = 9,230 MJ
Biogas energy input per year (@8,500 flh)	21,795 MW h =78,462 GJ
Energy density input biomass per year (@ 74% ratio)	106,353 GJ

Net calorific value algae	18 – 23 GJ/t
Net calorific value maize	16.5 GJ/t
Needed algae dry mass	4,624 – 5,909 t
Needed algae dry mass per kW h biogas	0.21 – 0.27 kg
Needed algae dry mass per kW h electricity	0.54 – 0.7 kg
Needed maize dry mass	6,445 t
Needed maize fresh material (@ 27.2% oTS)	23,697 t
Needed maize fresh material per kW h biogas	1.09 kg
Needed maize fresh material per kW h electricity	2.79 kg
Necessary aqua culture area (@ 73 t/ha)	63 – 81 ha
Necessary maize culturing area (@ 40 t/ha)	592 ha
Land area ratio: maize vs. algae (avg.)	8.2

The calculation is based on the assumption that the biogas output of algae is as high as the biogas output of maize. It takes into account that the plant has a desired electrical output. Together with electrical and thermal efficiencies of a state of the art combustion engine the losses and the needed input power can be calculated. As a calculation base it is further assumed that the engine produces energy for 8,500 full load hours per year. These assumptions lead to an hourly input of 2,564 kW h (i.e. 9,230 MJ). For the given amount of full load hours of production energy of 78,462 GJ is necessary.

$$P_{el} + P_{th} + P_{loss} = P_{input}$$

$$1{,}000\ kW + 1{,}000 * \left(\frac{44}{39}\right) kW + 1{,}000 * \left(\frac{17}{39}\right) kW = 2{,}564\ kW$$

$$2{,}564\ kW\ h * 8{,}500\ h = 21.795\ GW\ h = 78{,}461.5\ GJ$$

In order to calculate the biomass input which is needed to produce biogas with the desired energy density biogas yields of approximately 74% of the input biomass are assumed (see 3.2.3, Table 23); this leads to a needed amount of biomass with an energy density of 106,353 GJ.

$$78{,}461.5\ GJ * \left(\frac{1}{0.738}\right) = 106{,}353\ GJ$$

With the help of the net calorific values of algae (i.e. between 18 and 23 GJ/t) and maize (i.e. 16.5 GJ/t) the dry mass of the substrates can be calculated, namely between 4,624 and 5,909 tonnes of algae and 6,445 tonnes of maize.

$$106{,}353\ GJ * \left(\frac{1}{18}\right)\frac{GJ}{t} = 5{,}909\ t \text{ ... algae input (low net CV)}$$

$$106{,}353\ GJ * \left(\frac{1}{23}\right)\frac{GJ}{t} = 4{,}624\ t \text{ ... algae input (high net CV)}$$

$$106{,}353\ GJ * \left(\frac{1}{16.5}\right)\frac{GJ}{t} = 6{,}445\ t \text{ ... maize input (dry mass)}$$

With a percentage of 27.2% concerning total organic solids (i.e. oTS=27.2%) for maize this figure corresponds to 23,697 tonnes of fresh material of maize.

$$6{,}445\ t * \left(\frac{1}{0.272}\right) = \ 23{,}697\ t$$ ... maize input (oTS=27.2%)

Assuming that aqua cultures are capable of producing 73 tonnes of algae biomass per hectare compared to a yield of 40 tonnes of fresh material of maize per hectare the water and land areas can be calculated; it is 63 to 81 hectares for algae ponds and 592 hectares for maize.

$$5{,}909\ t * \left(\frac{1}{73\,\frac{t}{ha}}\right) = 80.94\ ha$$ ... algae area (low net CV)

$$4{,}624\ t * \left(\frac{1}{73\,\frac{t}{ha}}\right) = 63.3\ ha$$ ... algae area (high net CV)

$$23{,}697\ t * \left(\frac{1}{40\,\frac{t}{ha}}\right) = 592.4\ ha$$ ... maize area

Taking an average of about 72 ha for algae related to 592 ha for maize this means that maize needs eight times the area of algae to produce a comparable output.

$$592.4/\left(\frac{63.3+80.94}{2}\right) = \frac{592.4}{72} = 8.212$$

Furthermore, the mass equivalents for one kilowatt hour of electricity are calculated; they range between 0.54 and 0.7 kg of algae biomass and about 2.79 kg of maize fresh material, respectively.

$$\frac{5{,}908{,}510\ kg}{8{,}500{,}000\ kW\ h} = 0.695\,\frac{kg}{kW\ h}$$ ... algae (low net CV)

$$\frac{4{,}624{,}051\ kg}{8{,}500{,}000\ kW\ h} = 0.544\,\frac{kg}{kW\ h}$$ ... algae (high net CV)

$$\frac{23{,}697{,}233\ kg}{8{,}500{,}000\ kW\ h} = 2.788\,\frac{kg}{kW\ h}$$ ... maize

3.2.6 Waste Heat Recovery in Algae Pond

Most algae which are suitable for energy production purposes have their optimum yields when grown at 30 – 35 °C (see 3.1.3.1.5). The schema of an algae and biogas powered CHP plant, which is shown in Figure 19, shows that parts of the waste heat can be used to heat up the water of the algae culture for an optimized algae growth. The following calculation estimates the energy needed for algae ponds. It is estimated that the ponds have a depth of 50 centimeters. One square meter of the pond then contains 500 liter water. The heat capacity of water is 4.187 kilojoules per kilogram mass and degree Kelvin. (i.e. $c_{p\,water} = 4.187\ kJ/kg * K$);

500 liters of water require the energy of 2,093 kilojoules to be heated up by one degree Kelvin ($\text{Energy}_{\text{water } 500} = 500\ \text{kg} * 4.187 \frac{\text{kJ}}{\text{kg}*\text{K}} = 2{,}093.5 \frac{\text{kJ}}{\text{K}} = 581.5\ \frac{\text{W h}}{\text{K}}$).

Assuming that 500 liters of water (i.e. one square meter with a depth of 50 centimeters) have to be heated up by one degree every hour throughout the year (i.e. for 8,500 hours) this process consumes approximately 5,000 kilowatt hours per year.

3.3 Practical Applications

This section shows two practical scenarios for an algae based electricity production. The first one introduces algae as a possible alternative fuel for an existing biogas CHP plant in Lower Austria, Austria. The second one describes a schema for a municipal wastewater treatment system involving algae to produce electric energy.

3.3.1 Algae as an Alternative Fuel for an Existing Biogas CHP plant

Using algae as energy producer does not necessarily mean building new power plants. Algae may also be utilised as an alternative fuel for existing biogas facilities. The following example describes an existing biogas plant in Lower Austria, Austria. The data is taken from interviews with Mr. Andreas Blochberger (owner and operating company) and Dr. Ortner (system architecture, project development) (Blochberger, 2010), (Ortner, 2010).

3.3.1.1 The Project

The following table characterises the biogas plant in figures. The plant consists of a one stage biogas fermentation unit with an intake of 33,000 tonnes of maize per year. The electricity and heat production are structured in three similar lines.

Table 25: Biogas plant example Ziersdorf, Lower Austria
(Blochberger, 2010), (Ortner, 2010)

Characteristics	Details
Type of biogas plant	One stage biogas fermentation
Electricity production	Combustion engine
Heat production	Heat exchanger
Number of electricity production lines	3
Electric output	3 * 500 kW
Thermal output	Ca. 3 * 550 kW
Operating hours (flh)	8,000
Electricity production	12,000,000 kW h per year
Heat production	12,360,000 kW h per year

Biomass intake	33,000 tonnes per year
Biomass intake per kW h electricity	2.75 kg
Cost for biomass per kW h electricity	6 € ct (2009); 12 € ct (2010)
Feed-in tariff per kW h electricity	14 € ct
Cost for biomass per kg (calculated)	4.4 € ct (2010)
Biomass type	Maize (@ yields of 30 – 40 tonnes/ha/yr)
Needed agricultural area for biomass	825 – 1,100 ha
Theoretical algae area (see Table 24)	110 ha

The characteristics of the plant (see Table 25) match very well with the calculated values of the theoretic calculation in the previous chapter 3.2.5; the plant demands 2.75 kilograms of fresh material per kilowatt hour of electricity.

3.3.1.2 Current Situation

According to the operator the economic situation for the particular plant is not very good in Austria at the moment. The feed in tariff for the produced electricity is 14 € cents per kilowatt hour. In contrast, the cost for maize fresh material which is equivalent to an output of one kilowatt hour has increased from 6 € cents to 12 € cents within the last year. Due to the doubling of the costs for the biomass material the operation of a biogas plant is hardly feasible at the moment.

3.3.1.3 Algae Alternative

The usage of algae biomass might be an alternative to maize fresh material. This could decouple the fuel costs from the maize price development. In addition, the land area which is necessary to grow the biomass input for the biogas plant could be reduced by nearly 90% (see land area ratio, Table 24). Of course, there are some prerequisites which have to be fulfilled to switch to algae biomass. It should be possible to build water ponds in the surrounding area of the biogas plant; the ponds need a water source to be filled initially and to compensate evaporation losses. It is also possible to utilise algae and traditional biomass sources in combination. Table 25 lists the theoretically needed algae aquaculture area for a total replacement of maize, namely 110 hectares. However, a combination of half maize and half algae biomass might lead to a saving of agricultural areas as high as 500 hectares; instead, 55 hectares would be needed for an aquaculture. Beside the usage for heating the fermenters, the waste heat of the plant can be utilised for the pre heating the water inflow into the ponds.

3.3.2 Municipal Wastewater Treatment in Combination with Algae

Algae can be grown in waste water delivering necessary nutrients for an optimum growth. That way, existing treatment plants could be used to grow biomass.

3.3.2.1 Municipal Wastewater Treatment

Figure 20 shows the schema of a waste water treatment plant involving algae. The data is taken from John R. Benemann (Benemann, 2009).

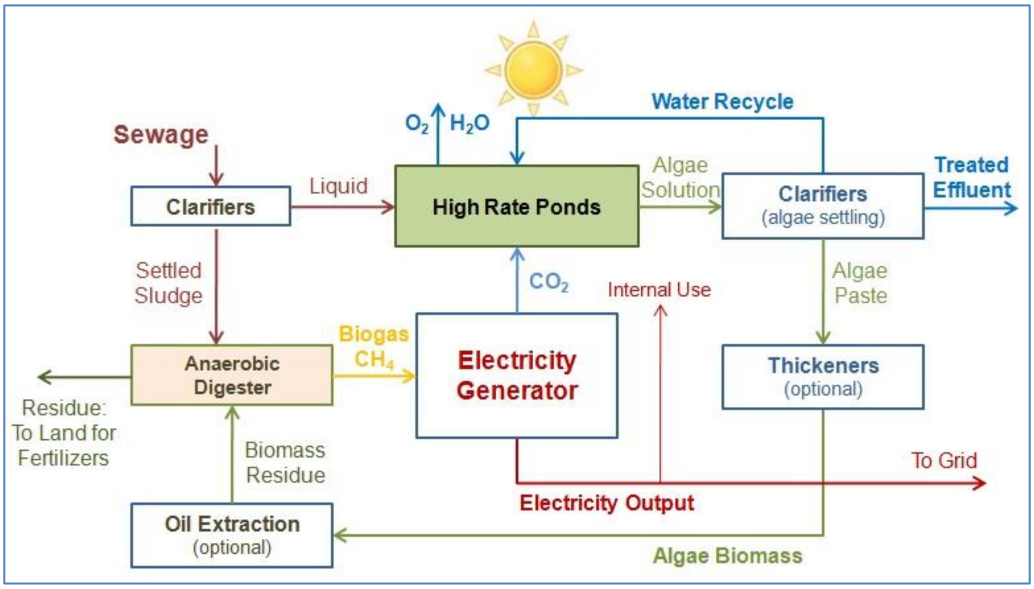


Figure 20: Schema of municipal waste water treatment using algae (Benemann, 2009), adapted

According to the schema the waste water input is clarified at the first stage. The liquid sewage is lead to the algae pond; algae are used to capture nutrients which are contained in the sewage. Sewage sludge (i.e. the solid parts of the waste water) gets fed into the anaerobic fermentation unit. At the pond site, parts of the grown algae solution are taken out of the aquaculture and are brought to clarification ponds. Algae biomass is collected (see section 3.1.3.3) whereas liquid fractions flow out in form of treated effluent; parts of the liquid are fed back to the algae pond (water recycling). In further steps algae biomass is fed in to the fermenter; together with the sewage sludge it is converted into biogas. Fermentation residues are used as agricultural fertilizers. The biogas powers an electricity generator as described in sections above; flue gas is fed into the algae ponds, electricity is fed into the grid.

3.3.2.2 Evaluation

The described usage of algae in wastewater treatment systems has several positive effects. Firstly, it augments and optimises existing treatment systems which are in place in large numbers around the world. Secondly, this system design involves a reuse or nutrients which may overcome two important obstacles in growing algae, namely the issues concerning the supply of algae growing systems with water and nutrients. Having in mind that algae need phosphorus and nitrogen to grow optimally this means that the cost for expensive chemicals can be saved. At that, it is even possible to achieve “negative” costs concerning those chemicals by filtering them out of waste water streams.

3.4 Economic Aspects

This chapter aims to emphasise the economic aspects of algae as energy producers in the sense of the practical examples as described in the chapters before, namely the usage of algae in existing biogas combined head and power (CHP) plants with on site biogas production. From this point of view it is not necessary to develop projects starting at zero which is economically dangerous as the research and development process concerning algae is at a very early stage at the moment. The following considerations assume that the existing biogas plant project is organised in a way that a project developer together with a construction company and investors set up the project and build the plant. Once the plant is ready to operate it is operated and maintained by an operating company. The raw feedstock which is needed to run the plant is obtained from local sources, for instance, from nearby farmers. This is necessary because of the enormous land area (approx. 600 hectares of land for an electric output of 1 MW in the case of maize) combined with the needed infrastructure to grow and harvest the energy crops including the delivery of the raw biomass to the plant site (i.e. agricultural machinery, harvesting personnel, transport equipment). As a result the biogas plant operator is dependent on market prices of the biomass which may bear fatal economic risks.
The usage of algae technology makes it possible to set up projects differently. Firstly, the production of the feedstock using pond systems is rather simple. Secondly, it consumes only 10% of the land area when compared to conventional biomass, for instance, maize. Finally, the growing and harvesting process is a continuous and ongoing procedure which offers the possibility to integrate the biomass production into the biogas plant system. This leads to a completely different

project scenario with almost no dependency on feedstock market prices. Although some conventional feedstock is needed also in this case as a co-fermentation substrate the main biomass source can nevertheless be obtained avoiding market price dependencies.

3.4.1 Upgrading Existing CHP Plants

Upgrading existing CHP plants for the usage of algae influences the costs in the following way. Firstly, the aquaculture has to be set up. With respect to the sizing of the ponds it can be estimated that a CHP plant with an electric output of 1 MW requires between 63 and 81 hectares of water surface for a complete supply with algae (see Table 24). As mentioned previously (section 3.2.4) at least 3% of the biomass input of the fermenter should be realised by using non algae substrates. Assuming that 90% of the biomass input consists of algae and that the rest is provided by using maize this means that a pond area of 56 to 73 hectares has to be planned. The maize input reduces from 24,000 (see Table 24) tons to only 2,400 tons of maize. In areas with long and cold winters with almost no algae growth it can be necessary to hold a certain amount of biomass on stock in order to compensate this fact. Of course, it could be taken into consideration to use manure or biowaste to keep the costs down. These considerations are excluded in the following calculations.

Secondly, the pond system has to be equipped with various technical units such as paddles stirring the water body, measuring units to control the culture quality (i.e. temperature, pH and chemical composition) and a harvesting unit. A water supply has to be built to provide the ponds with fresh water compensating evaporation losses. The inflow of the water has to be equipped with a pre heater which is powered by the waste heat of the combustion engine. A pipe system placed within the ponds brings exhaust gases to the water body and delivers some portions of extra heat as well as carbon dioxide. The transport of the harvested algae biomass to the fermenters can be realised via pipe systems. However, the fermenters and the combustion unit do not have to be changed with the exception of equipment to redirect waste gases and waste heat towards the ponds.

Finally, there are additional costs for the pond maintenance and operation as well as for nutrients which have to be added to the algae culture. The main nutrients are nitrogen and phosphorus.

3.4.2 Cost Comparison – Conventional Plant vs. Algae Driven Plant

The following scenario shall find out if it is financially feasible to upgrade an existing biogas CHP plant located in Lower Austria as mentioned in section 3.4.1 from using conventional biomass, namely maize to the usage of algae. The scenario is characterised by three main assumptions: Firstly, before the upgrade the raw biomass is purchased from farmers at market prices. Secondly, 90% of the previously used feedstock should be replaced by algae biomass. Finally, the algae growing system should be integrated into the biogas plant. This way the biogas production can be decoupled from marked driven feedstock prices as far as possible as the necessary biomass feedstock can be produced on site in an autarkic way. The following table gives an overview of the cost factors which change due to the modified biomass supply.

Table 26: Changing cost factors: biogas plant upgrade from maize to algae

Changing costs	Order of magnitude
Additional investment costs	
Purchase of land area for ponds	For Lower Austria the prices for agricultural area range between 1.00 and 1.50 € per square meter for remote locations and up to 5.00 – 6.00 € for locations in the near of cities[36]. **Minimum: 10,000 – 15,000 €/ha**
Investment for pond system with paddles including additional equipment	**NREL – ASP based on a 400 ha system** (Sheehan, et al., 1998 p. 239) **50,000 $/ha** **AmericanEnergyIndependence** (Briggs, 2010) **80,000 $/ha**
Additional operating costs	
Power demand, nutrients, additional CO_2, labour and overheads	**NREL – ASP based on a 400 ha system** (Sheehan, et al., 1998 p. 239) **10,000 – 16 000 $/ha/yr** (net operating costs)
Savings on fuel costs	
Maize (@ 4.4 € ct/kg maize)	90% of the costs for conventional feedstock

The figures in the table above may be taken as an indication of possible orders of magnitude for the upgrade of an existing biogas plant in Lower Austria. The purchase costs for the needed land area are realistic and current prices. The investment costs for building a pond system are based on the close out report concerning the ASP program of NREL which has been published years ago for the

[36] The price information has been provided by the chamber of agriculture for Lower Austria (Mr. Weichselbraun) on August 6, 2010.

American market (Sheehan, et al., 1998) and on a cost estimation published by Michael Briggs (University of New Hampshire, Physics Department) on the web site of the independent organisation “America Energy Independence” (Briggs, 2010), respectively. The operating costs running an open pond algae cultivating system are again based on the NREL report (Sheehan, et al., 1998).

The details for the biogas powered CHP plant which is to be upgraded in the scenario are noted in section 3.2.5 (see Table 24). For an electric output of 1 MW the plant requires a maize input of 24,000 tons/year. 90% of the feedstock is replaced by algae biomass. Subsequently, the maize input reduces to 2,400 tons/year. The size of the pond system ranges in an area of 56 to 73 ha.

In the scenario the investment period is set to 20 years. The investment costs are portioned adequately; the constant annuities of the investments are calculated on a weighted average cost of capital (WACC) of a certain amount. The following calculations involve some variations of the most important influence factors: growth index of the maize price and operating costs, feedstock replacement ration and needed pond area, respectively. The costs for land and infrastructure are set to fixed values according to values in Table 26. Initially, the needed land area is set to the worst case value of 73 ha.

Table 27: Calculation assumptions

Assumption	Value	
Needed land area for OPS		**73 ha**
Costs for land area	**15,000 €/ha**	1,095,000 €
Yearly rate (based on WACC)		**119,953 €/yr**
Cost for OPS	**65,000 €/ha**	4,745,000 €
Yearly rate (based on WACC)		**519,798 €/yr**
Operating costs for OPS	**10,000 €/ha/yr**	**730,000 €/yr**
Maize price	4.4 € ct/kg	
Maize input	Before: 24,000 t/yr → After: **2,400 t/yr** →	**1,056,000 €** **105,600 €**
Index maize price		**7% per year**
Index for other operating costs		**2% per year**
Interest rate		**9% per year**
Investment period		**20 years**

Table 27 lists the assumed influence factors. The operating costs for the OPS are set to 10,000 € per hectare and year; the capital costs are set to 9%, the price index for the pond’s operating costs is set to 2%. The maize price is assumed to increase by 7% per year. Influence factors for an increasing maize price are escalating feed and food demands as well as the expectable growing demand for biomass as energy carrier. Furthermore, it is assumed that 90% of the maize feedstock is replaced by algae biomass. The figures marked orange will be varied in order to show the sensitivity of the calculation model later on.

Table 28: Project calculation: algae upgrade (unit €)

Year	Land cost [€] annuities	OPS cost [€] annuities	Maize Price [€ ct / kg] index 7% pa	Fuel Cost [€] Maize only	Fuel Cost [€] 90% Algae	Fuel Cost Savings [€]	Op. Cost OPS [€] index 2% pa	Balance [€]
1	-119,953	-519,798	4.40	-1,056,000	-105,600	950,400	-730,000	-419,351
2	-119,953	-519,798	4.71	-1,129,920	-112,992	1,016,928	-744,600	-367,423
3	-119,953	-519,798	5.04	-1,209,014	-120,901	1,088,113	-759,492	-311,130
4	-119,953	-519,798	5.39	-1,293,645	-129,365	1,164,281	-774,682	-250,152
5	-119,953	-519,798	5.77	-1,384,201	-138,420	1,245,781	-790,175	-184,146
6	-119,953	-519,798	6.17	-1,481,095	-148,109	1,332,985	-805,979	-112,745
7	-119,953	-519,798	6.60	-1,584,771	-158,477	1,426,294	-822,099	-35,556
8	-119,953	-519,798	7.07	-1,695,705	-169,571	1,526,135	-838,541	47,843
9	-119,953	-519,798	7.56	-1,814,405	-181,440	1,632,964	-855,311	137,901
10	-119,953	-519,798	8.09	-1,941,413	-194,141	1,747,272	-872,418	235,103
11	-119,953	-519,798	8.66	-2,077,312	-207,731	1,869,581	-889,866	339,963
12	-119,953	-519,798	9.26	-2,222,724	-222,272	2,000,451	-907,663	453,037
13	-119,953	-519,798	9.91	-2,378,314	-237,831	2,140,483	-925,817	574,915
14	-119,953	-519,798	10.60	-2,544,796	-254,480	2,290,317	-944,333	706,232
15	-119,953	-519,798	11.35	-2,722,932	-272,293	2,450,639	-963,219	847,668
16	-119,953	-519,798	12.14	-2,913,537	-291,354	2,622,184	-982,484	999,948
17	-119,953	-519,798	12.99	-3,117,485	-311,748	2,805,736	-1,002,134	1,163,851
18	-119,953	-519,798	13.90	-3,335,709	-333,571	3,002,138	-1,022,176	1,340,210
19	-119,953	-519,798	14.87	-3,569,208	-356,921	3,212,288	-1,042,620	1,529,916
20	-119,953	-519,798	15.91	-3,819,053	-381,905	3,437,148	-1,063,472	1,733,924
Sum	**-2,399,068**	**-10,395,960**		**-43,291,240**	**-4,329,124**	**38,962,116**	**-17,737,080**	**8,430,008**

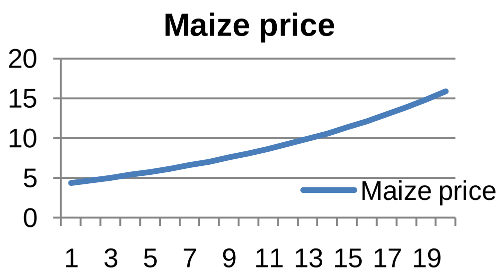


Figure 21: Maize price development at an index of 7% per year

Table 28 shows the financial balance over the investment period. The constant annuities (*R*) of the costs for land and infrastructure are calculated by the following formula. S_0 defines the value of the investment; *i* symbolises the interest rate; *n* defines the investment period (20 years).

$$R = S_0 * \frac{i * (1+i)^n}{(1+i)^n - 1}$$

The maize price increases based on a growth index of 7% per year. Figure 21 shows the assumed development of the maize price during the investment period. The expected fuel costs for a conventional operation of the plant (24,000 tons of maize per year) are listed in the column *"Fuel Cost – maize only"*. The column *"Fuel Cost – 90% algae"* notes the costs for the residual amount of maize used for co-fermentation in the upgrade scenario (2,400 tons of maize per year); *"Fuel Cost – savings"* illustrates the fuel cost savings for maize which can be gained by using algae instead of maize feedstock. The column *"Op. cost – OPS"* depicts the operating expenses for the open pond algae cultivating systems which are assumed to increase by 2% per year; the column *"Balance"* displays the yearly sum of expenses and savings for the upgrade scenario.

During the first years (year one to year seven) the balance is negative which means that the annual costs for the algae upgrade exceed the savings on conventional feedstock. Starting with year eight the savings top the yearly expenses. Overall, the upgrade of the biogas CHP plant from maize to algae biomass shows a positive balance at the given influence factors.

However, if the growth index for the increasing maize price is decreased from 7% to a value of 5% per year the overall result decreases from approx. 8.4 million € to about 900,000 €. This means that the assumed increase of the maize price is essential for an economic profitability of the upgrade. Lowering the replacement ratio of the conventional feedstock from 90% to 80% has significant but not dramatic influences on the overall result. Further details can be seen in the following table.

Table 29: Changing influence factors and their effects: sensitivity

Influence factor	Change	Changed result	Sensitivity
Initial values	**Reference**	**8,430,000 €**	
Index for maize price	**7% → 5%**	**893,775 €**	**High**
Percentage of maize biomass replacement	2,400 t/yr → 5,000 t/yr **90% → 80%**	**3,740,123 €**	**Significant**
Index for operating costs OPS	**2% → 5%**	**2,028,941 €**	**Significant**
Needed land area	**73 ha → 70 ha**	**9,684,752 €**	**Low**

Nevertheless, it can be stated that the upgrade from maize to algae biomass is economically feasible at certain circumstances.

3.4.3 Alternative Cost Estimation

According to a cost estimation published by the IWA, an online platform for the global water community (IWA - International Water Association, 2010), the production cost for producing 1 kg algae biomass is 2.95 $ for closed photobioreactors (PBR) and 3.8 $ for open pond systems at a production capacity of 100 tons per year. If the annual production reaches a volume of 10,000 tons the production cost decreases to 0.47 $ (PBR) and 0.6 $ (open pond systems) per kilogram, respectively.

The plant with an electricity output power of 1 MW in the example above requires an algal biomass input of approx. 6,000 tons @ 0.6 € per kilogram compared to a maize feedstock consumption of approx. 24,000 tons @ 0.044 € per kilogram (see Table 24). Assuming that the lower cost level as mentioned by IWA can be achieved and under the assumption that euro prices are comparable with dollar prices the biomass feedstock prices for an output of 1 MW_{el} can be calculated:

Algae: $6{,}000{,}000\ kg\ * 0.6\ \frac{€}{\mathrm{kg}} = 3{,}600{,}000\ €$

Maize: $24{,}000{,}000\ kg\ * 0.044\ \frac{€}{\mathrm{kg}} = 1{,}056{,}000\ €$

It can be seen that the price of algae biomass is about three and a half times as high as the price of maize.

The alternative cost estimation shows a difficult economic situation of an upgrade from maize to algae biomass if only the current maize price situation is considered. Assuming that maize prices will increase steadily over the next years the picture changes immediately.

3.4.4 Summary of Economic Considerations

With respect to the price level of conventional feedstock types and the stage of development of algae growing technology it may difficult or risky to switch the biomass feedstock of existing biogas plants to an almost exclusive usage of algae biomass at the current point of time. However, it has to be stated that on the one hand algae technology is being developed globally by an uncountable number of projects which will lead to lower production costs. In addition, algae promise to achieve a significantly higher productivity in near future (see Table 21). The calculations use a conservative productivity of $20\ g/m^2/day$ based on a PE of 2%. With a theoretic maximum of 9% the productivity could reach $60\ g/m^2/day$ in Austria and $93\ g/m^2/day$ in Spain. On the other hand the global situation with respect to a food vs. feed discussion is supposed to lead to rising prices for conventional feedstock types. Furthermore, algae biomass may not only be used as an energy producer. If parts of the produced algae biomass are used for food or pharmaceutical purposes where significantly higher prices can be achieved these additional earnings may compensate the higher production costs of algae biomass. Finally, it has to be mentioned that algae cultures may be placed on areas which are not suitable for agricultural scopes which can help lowering the production costs.

4 Algae as a Renewable Energy Source – Answers

This chapter condenses the collection of facts in combination with the data the practical examples as pointed out in chapter 3. It gives answers to the main questions of the Master Thesis (see 1.2).

4.1 Algae vs. Conventional Feedstock

How do algae differ from other plants?

4.1.1 Physiology and Species

The main difference between algae and higher plants is the physiologic structure. Algae do not build roots or stems. Instead algae consist of single cells or groups of single cells. In general, algae are photoautotroph which means that they have the ability to generate organic matter using inorganic components, such as water, carbon and other elements. Algae exist in almost uncountable numbers of species. Unlike conventional biomass feedstock only a small percentage of the existing species has been studied in detail. Algae are classified according to their characteristics (see section 3.1.2.2) and differ with respect to their chemical composition.

4.1.2 Growth

The growth of algae cells is very effective because every single cell of a certain species is similar to the other one. Growth means doubling of cells which then may group in different structures. Each cell is fertile and can generate new cells. The doubling rate is high and occurs in the area of a few days which leads to high growth rates compared to higher plants. The photosynthetic efficiency (PE) of algae is up to 9% compared to 1% for higher plants. This means that, for instance, in Austria algae can generate a daily average of up to 62 grams of biomass whereas higher plants generate 7 grams per day. In regions with higher irradiation, for instance, in Spain algae may generate 93 grams of biomass per day; higher plants in Spain reach 10 grams (see Table 21 in section 3.2.2).

4.1.3 Habitats

Algae have a very long history on earth. As a result different species adapted to almost every thinkable water body have developed. Algae can be found in marine water, in fresh water bodies and in shallow water. Compared to higher plants algae have the broadest range of possible habitats. Psychrophilic species live in cold environments with temperatures down to 0 °C. Mesophilic species populate water with temperatures from 20 – 30 °C. Thermophilic species can live in environments with up to 70 °C. Beside water and carbon dioxide algae require light and some nutrients. As a matter of fact they can be grown using areas which are not suitable for agricultural purposes; this excludes algae growing systems from the food vs. feed discussion.

4.1.4 Summary

In comparison with higher plants algae show a variety of different species populating almost every type of water in almost all temperature regions. As long as water, light, carbon dioxide and some nutrients are supplied algae can be grown using any kind of otherwise unused areas. The fact that algae are much more efficient in generating biomass than higher plants makes it very interesting for researchers around the world to study possibilities to utilise algae for energy production (see Annex 1 and Annex 2 for examples). The ability to grow endlessly while doubling the biomass within a few days is another advantage of concentrating on algae biomass.

4.2 Generation of Algae Biomass

How can the flows of biomass generating components (light, water, carbon dioxide) be characterised?

The generation of algae biomass is realised by light-fed metabolic processes in the course of the complex of photosynthesis. Photosynthesis consists of two main sub processes, namely the *light dependent group of reactions* which dissociate water with the help of impelling light and enzymes into hydrogen and oxygen charging intracellular energy carriers on the one hand; on the other hand there is the *light independent complex of reactions* which utilises the previously charged energy carriers to fix carbon from the ambient air and to form sugars. That way, photoautotrophic organisms are able to generate organic matter by using light energy and inorganic elements.

4.3 Efficiency of Algae as Energy Storage

How efficient can algae transform solar energy into biomass?

Algae show a high photosynthetic efficiency of up to 9%. This means that up to 9% of the impelling light is stored in the form of biomass (see 3.1.2.3.1.5). Algae are high effective bio storage systems for solar energy. In addition, algae are able to grow continuously. This fact enables algae growing systems to be integrated directly into energy generation systems avoiding seasonal harvesting followed by holding biomass on stock for longer periods of time as practiced with conventional feedstock.

4.4 Selection of Algae Strains

What are the aspects for the selection of utilised algae strains?

Depending on the desired conversion of algae biomass into secondary energy certain characteristics of algae strains are more important than others. For instance, the biodiesel research tries to select strains with higher lipid contents. Unfortunately, strains with high oil contents tend to grow slower than algae with lower lipid fractions. In general, it has to be stated that the strains which have been under investigation concerning their qualities as energy producers during the last centuries are strains that have been described by biologists for non energy related reasons. As there are so many strains which have not been discovered by now an energy focused research may bring up strains which are even more suitable for producing energy than known strains. The ideal strain of energy related algae research is an algae strain which grows fast, has the ability to grow in mass cultures, has the ideal chemical characteristics and is optimally adapted to the prevailing environmental conditions. There has been research for manipulating the genetics of known strains in order to enhance lipid contents (Sheehan, et al., 1998). However, genetically engineered strains have to be isolated from the environment to avoid contamination of natural strains; this complicates the handling of algae biomass. A more sustainable method of optimising algae characteristics is to expose algae cultures to certain types of nutrition stress, namely nutrition starvation or nutrition limitation (see 3.1.3.1.4).

4.5 Energy Related Use of Algae

How can algae be utilised for energy purposes?

Due to the fact that algae grow as single cells within water the grown biomass is very homogenous. The direct use of algae paste within fermenters in order to generate biogas is the most economic way to transform the stored energy into useful energy, such as electricity. This kind of usage means a biochemical conversion of biomass into secondary energy. Especially in America research tries to profit by the high lipid (i.e. oil) content of some algae strains to harvest bio crude oil which is transformed into biodiesel and jet fuels. With respect to oil algae deliver three to four times the oil yield per hectare and year than the best species of higher plants, namely palm oil and Chinese tallow (see 3.1.4.2). The extraction of oil describes a physical-chemical utilisation of biomass. Other forms of physical-chemical transformations are gasification, pyrolysis and combustion of biomass. Details can be found at 3.1.6.

4.6 From Solar Energy to Biogas and Electricity

How does the logistic path of growing and harvesting of algae biomass look like?

4.6.1 Growing

There are different methods of growing algae in mass cultures. The algae cells can be grown in a *planktonic* way, namely free floating in water. Technical growing equipments are either open or closed systems. In open ponds (OP) algae are grown with contact to nature in shallow water. Typically the water depth is about 30 cm; paddles generate a steady water flow to provide stable and homogenous culture conditions. OP systems are relative cheap to build. However, these systems show some obstacles. It is possible that the algae culture is contaminated with local and possibly unwanted strains or that the system is populated by micro organisms which live on the cultivated algae. In addition, water evaporates which hinders an optimal CO_2 supply. As a matter of fact OP systems cannot compete with closed systems, the so called photobioreactors (PBRs) with respect to feasible productivity. PBR systems consist of mostly transparent plastic tubes which are exposed to the sunlight. The advantages are obvious. The culture parameters such as temperature, pH, nutrients concentration, flow velocity, oxygen outflow and even dark periods can be synthesised matching the selected strains. The initial system costs are higher compared to OP systems; nevertheless, the productivity is optimal (see 3.1.3.2). Alternatively the cells can be grown attached to rocks and plants, i.e. in a *periphytonic* way. In this case water circulates around carriers in open systems; the diatoms remain attached to the carriers (Van Aken, 2009). All growing methods have in common that it is crucial for an optimal output that some growing parameters are kept at ideal levels. Too strong light should be avoided; CO_2 and nutrients have to be provided sufficiently (see 3.1.3.1).

4.6.2 Harvesting and After-treatment

Algae grow continuously so the harvesting process is an ongoing business. The goal of the harvesting process is to collect algae paste. Open pond systems may be equipped with settling ponds where the biomass is concentrated, optionally induced by flocculants. The concentrated biomass can be pumped out of the ponds in the form of algae paste. PBR systems can be equipped with separation units which again deliver algae paste. Depending on the following utilisation of the biomass an after-treatment can be applied. For an oil production the lipid contents have to be separated from the residual biomass components. In some cases the paste has to be dried which is energy consuming. The most energy saving utilisation of biomass is the direct connection with a fermenting unit. In this case the high water contents of the biomass are advantageous (see 3.1.3.3).

4.7 Energy Balance of Electricity Derived from Algae Biogas

How can the total efficiency of an algae biogas powered electricity production be estimated?

In order to estimate the overall efficiency of an algae powered electricity generation using biogas as an intermediate product the following assumptions are made. Algae biomass should be fermented into biogas; the produced biogas should fuel a combustion engine which powers an electric generator. The data is taken from section 3.1.2.3.1.1 for the irradiation, 3.1.2.3.1.5 for the PE, 3.2.3.1 for the conversion efficiency of biomass into biogas and 3.2.5 for the conversion efficiency of biogas into electricity and heat, respectively.

Table 30: Total efficiency of algae derived electricity using biogas

Step	Assumptions	Results min	Results max
Solar irradiation per square meter	**1,000 W/m²**		
PE of algae	2% – 9%		
Power equivalent of **biomass**		**20 W/m²**	**90 W/m²**
Conversion efficiency: biomass to biogas	74%		
Power equivalent of **biogas**		**14.8 W/m²**	**66.6 W/m²**
Conversion efficiency: biogas to electricity	39%		
Power equivalent of **electricity**		**5.8 W/m²**	**26 W/m²**
Conversion efficiency: biogas to heat	44%		
Power equivalent of **heat**		**6.5 W/m²**	**29 W/m²**
Power equivalent (**electricity + heat**)		**12.3 W/m²**	**55.3 W/m²**

The input source of the estimation is the solar irradiation per square meter. Using the energy conversion efficiencies in the order of their occurrence in the course of the "generation" of electricity makes evident how much of the input energy is available per square meter of production area in the different production steps. It gets obvious that algae may deliver between 6 and 26 watts of electricity per square meter; this equals a percentage of between 0.6 and 2.6%. If the produced heat is utilised the percentage more than doubles to 1.2 – 5.5%. By the way, solar cells show typical maximum efficiencies of about 5 – 20% depending on the cell type.

4.8 Algae Potentials in Austria

How big is the potential for growing algae for energy purposes in Central European regions and especially in Austria?

Most algae strains which are suitable for energy production are mesophilic strains. This means that they have their optimal growth at water temperatures of 20 – 30 °C. They also grow at lower ambient temperatures, so the environmental requirements for growing mesophilic algae are fulfilled in the warm weather period. Especially in the case of open pond systems algae may be grown from March to October/November (see 3.1.3.1.5). Closed PBR systems may be used for a longer period because of the insolating effect which is provided by the closed culture circuit. Algae represent a concentrated form of stored solar energy. The example describing electricity production from biomass (see 3.2.5) demonstrates that the area which is needed to produce the required biomass can be reduced by more than 80% when using algae grown in OP systems instead of maize. The economic estimations concerning a switch from maize to algae biomass for the production of biogas (see 3.4) show that it can be economically feasible to upgrade to algae feedstock. The most important influence factor for an economic feasibility is the price for maize in relation to the expected operation costs for the cultivation of algae; in addition, it is crucial to replace as much maize as possible by algae biomass. The combination of the algae growing system with a waste water treatment plant delivering substantial amounts of nutrients may introduce a reduction of operating costs.

The following table combines the theoretic total efficiencies as estimated in section 4.8 with annual irradiation values of Austria and Spain (see 3.2.2).

Table 31: Potential for annual electricity output in Austria compared with Spain

Step	Assumptions	Results	
		PE 2%	PE 9%
Eastern Austria			
Solar irradiation per year (PVGIS)	**1,400 kW h/m²**		
Electricity output		**8 kW h/m²**	**36 kW h/m²**
Heat output		**9 kW h/m²**	**41 kW h/m²**
Sum		**17 kW h/m²**	**77 kW h/m²**
Spain			
Solar irradiation per year (PVGIS)	**2,100 kW h/m²**		
Electricity output		**12 kW h/m²**	**54 kW h/m²**
Heat output		**14 kW h/m²**	**61 kW h/m²**
Sum		**26 kW h/m²**	**116 kW h/m²**

If it is taken into account that the generation of electricity on a CO_2 neutral and sustainable base will gain importance and that algae productivity will achieve higher values within the next years it has to be said that the potentials for using algae as energy source are remarkable; this applies especially to warmer regions of Central Europe but also to Austria. Algae need less area to be grown as they show a much higher photosynthetic efficiency compared to conventional feedstock.

4.9 Competing Usage of Algae

What are the competing applications of algae besides energy production?

Algae are not only interesting for the energy business. Since ancient time algae – both microalgae and macroalgae – have been used as food, remedies and fertilizers. Food purposes are mainly covered by macroalgae. Microalgae, however, are cultivated globally in masses as a source for vitamins, omega-3 fatty acids, pigments and proteins for cosmetic and pharmaceutical industry (see 3.1.3). Algae biomass which is used for some of these applications, for instance, in the case of algae as a producer of high quality omega-3 fatty acids can be sold at very high prices. According to an interview with M. Mohr from Ecoduna (Mohr, et al., 2009) one litre of algae oil can be sold at prices which are the hundredfold of the prices of algae which are used for energy applications. Of course, for cosmetic applications the whole growing system has to be food safe using pure nutrients within PBR systems avoiding environmental contamination risks. Nevertheless, the achievable high price products made from algae have a strongly positive influence on the development of improved growing systems which then can be reused in the energy business. Flat panel PBR systems from Ecoduna (see 3.1.3.2.3.2) are a good example for such a development. Companies selling high price algae products finance the research and development of high-tech PBR systems. Once the development has been finished the systems can be produced at lower prices with makes the systems affordable for energy applications.

4.10 Roadmap for Algae Energy

How can the roadmap for utilising algae as an energy source look like?

Researchers and start up projects all around the world are experimenting with algae as alternative biomass source and energy producer. (Please refer to Annex 1 and Annex 2 for some examples). In the beginning of this new technology the cost factor for the development of economic feasible scenarios is essential. Therefore it is important to use synergy effects, for instance, by combining algae growing systems with waste water treatment systems. Waste water treatment is available in almost every municipality and is capable of delivering water and pond systems in conjunction with required nutrients (see 3.3.2). That way the operating costs of algae projects can be held low. Another option of introducing the new technology is to set up demonstration plants in order to find out if PBR systems or open pond systems offer advantageous growing systems matching the environmental conditions in a certain geographic area. As a next step the positioning of algae driven energy supply units could reach a grade of maturity to be rolled out as an interesting alternative to, for instance, regional biogas plants which are now fuelled by conventional feedstock. Existing biogas facilities do not require major changes if the biomass source is changed to algae with exception of a possible redirection of waste gases and waste heat towards the algae culture (see 3.2.6).

4.11 Core Question

In how far can algae based bioenergy contribute to our electric power supply?

The answers to the questions in chapter 4 underline the promising future of algae in their role as a very effective energy source, especially for electricity, in various facets. The high photosynthetic efficiency which exceeds the productivity of conventional plants by far ensures the ability of algae to support our growing demand for energy. Algae growing systems can be placed wherever there is enough light, water and CO_2. Due to their low demand for growing area in comparison with conventional energy crops, for instance, palm oil and maize algae can help avoiding the conversion of more forests into farm lands. In addition, algae can populate almost any type of water, from salt water over fresh water to shallow water and waste water. Especially in combination with waste water algae may help recovering nutrients which have to be separated from waste water by the use of chemicals by now. The use of algae systems in combination with biogas and electricity generation has the advantage to deliver universally usable electricity on the one hand and high grade fertilizer as a by product; in addition, growing algae releases free oxygen and fixes CO_2. The integrative usage of algae will lower the operating costs of algae growing systems, the usage of algae in combination with waste gases and waste water may even generate “negative” costs. This makes algae even more interesting as the future bioenergy producer.

5 Conclusions

This paper was intended to give a comprehensive overview on the fascinating world of algae as a versatile energy producer. From a biologic point of view algae are the most effective storage facilities for sunlight which exist on earth. The variety of described topics shows that there is no single solution concerning algae as a renewable and sustainable energy source. It is biology, physics, thermodynamics, chemistry and also economics which have to be considered when it comes to biomass utilisation in general and algae utilisation in particular. This paper tries to compile snapshots of these areas of expertise. A further goal of this compilation of facts is to tell science fiction from reality because some publications predict, for example, astronomical high oil yields based on algae. In order to do so the theoretic potential of algae biomass production has an important function. By calculating the maximum biomass yield of algae a very high potential can be verified; but there are also certain limits which have to be born in mind when working with algae: The most important fact is the 9% limit, this means that maximal about one tenth of the power of sunlight which meets a certain area can be stored in the form of biomass by algae. In addition, it has to be said that theoretic potentials can hardly be achieved in reality; it means very high efforts to overcome certain obstacles on the way to the maximum potential. Open pond systems are exposed to nature and can be contaminated; there are days with less or almost no sunshine; the temperature can exceed ideal conditions. PBR systems may overcome most of the OP related obstacles and show significantly higher productivity. Nevertheless, photobioreactors are much more expensive.

Howsoever, if only the half of the potential can be realised within the near future algae will be play a major role as energy storage systems. According to H. Hofbauer the solar radiation delivers 2,000 times the amount of energy which is used on earth today by irradiation (Hofbauer, 2009). Conventional plants which are currently used as energy carriers are able to store one percent of the sunlight; algae exceed these yields by far.

What are the Conclusions of this Paper?

Energy Demand and Electricity

Energy demand is expected to increase on a global base during the next decades. The electricity share of the total final energy consumption will continue gaining importance.

Sustainability, Algae Biomass, Efficiency and Agricultural Areas

Effected by vanishing fossil resources as well as by climate related global action plans sustainable energy resources will be of particular importance. Algae as the fastest growing and most energy efficient photoautotroph organisms storing solar energy are predestined to fulfil these needs. Algae can grow in non potable water on any flatland requiring only light, CO_2 and some nutrients. That way algae save valuable potable water as well as farm lands. Especially these saving potentials stand for an applied sustainability.

Various Energy Conversion Paths and Electricity

Algae biomass can be transformed into various products depending on the desired form of secondary energy. Algae deliver plant oil as a base for biodiesel and bio jet fuels; this conversion path is very important for researchers in the USA. Furthermore, algae are an ideal input substrate for anaerobic fermentation processes delivering biogas on the one hand and fermentation residues as a valuable agricultural fertilizer on the other hand. Even hydrogen is a possible output product. Practically any of the various conversion methods which have been developed in the biomass area in the past, for instance, gasification, pyrolysis etc. can utilise algae as input material without significant changes in order to produce important products which are fossil based at the moment: Ethylene, ethanol, formaldehyde and so forth. Electricity from algae biogas is one of the most effective secondary energy forms which may be algae powered.

Non Energy Related Usage

Currently, algae are mainly used in foods, pharmaceutical commodities and medical applications. Non energy related utilisation of algae has already reached an industrial scale. Therefore the energy related usage of algae can benefit from the R&D which has already been done.

No Rocket Science – It is Nature

Compared to other high-tech renewable technologies algae cultivation is not a big secret in general. Algae represent organisms which have inhabited our planet for millions of years; actually, there is practically no water environment which cannot be populated by algae. As a matter of fact cultivating algae is maximal scalable. Small micro ponds are generally comparable to large growing systems. It is only the size that changes. Start up projects can be realised easily because the base technology is simple on the one hand and because very detailed knowledge is available in literature and on the Internet.

Positive Side Effects

Growing biomass in general has many positive side effects. Biomass generation processes produce oxygen and bind CO_2. Algae cultivation even offers more advantages: algae may clean waste water and so are able to recycle valuable nutrients such as sulphur and phosphate for free. The combined usage of waste water treatment and algae culturing appears to be very promising.

Numerous Research Projects

Numerous algae projects around the globe verify the expected potentials of algae as an important future energy carrier. The USA mainly concentrates on algae oil as an intermediate product for biodiesel and jet fuels whereas Europe also focuses on algae driven biogas production. The huge number of research projects guarantees a fast development of economically feasible ways to use algae as an important energy carrier also in the near future.

Situation in Austria

At the current point of time there are no remarkable energy related algae projects in Austria. As a matter of fact it would be very interesting to study the potentials of algae under our local environmental conditions. The growing number of worldwide algae activities may initiate similar (start up) projects and demonstration plants in Austria and the Central European Countries as well to gain region specific experience in the fascinating field of algae.

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Annexes

Annex 1 – List of Web Sites Covering Algae Biomass

A Google search for algae biomass returns 1.010.000 hits (current as of August 5, 2010). In the course of writing this paper the author screened many of the listed web resources. The following table lists the most interesting and relevant websites in the growing field of algae biomass for energy purposes.

Table 32: Websites covering algae biomass

URL	Description	Country
http://advancedbiofuelsusa.info/	Site promoting advanced biofuels; offers related news organised by country, R&D and educational information.	USA
http://algaeforbiofuels.com/	Site about algae green-chemicals and biofuels business by Prof. Aecio D'Silva (University of Arizona)	USA
http://algelab.org	"Do-It-Yourself Biofuels and Superfoods" – site by Berkeley, CA algae enthusiast offering a forum and a video on algae ponds.	USA
http://americanaquabiotech.com/	Site about "Scientific-Technical Knowledge, People Leadership Skills, and Marketing Expertise" by Prof. Aecio D'Silva (University of Arizona) covering algae based plastics.	USA
http://biofuelsrevolution.com/	Site about sustainable, clean and profitable renewable energy solutions by Prof. Aecio D'Silva (University of Arizona). Amongst other topics this site covers biogas topics.	USA
http://iwawaterwiki.org/xwiki/bin/view/Main/	IWA Water Wiki is an online location for the global water community. It covers water related topics including algae.	UK
http://www.algae.wur.nl/UK/	Research on algae by Wageningen UR University, Netherlands; the web site offers detailed information on algae related research topics	Netherlands
http://www.algaeindustrymagazine.com/	Online magazine offering interactive content related to algae and biofuels	USA

http://www.algaeventuresystems.com/	Company web site offering information including detailed picture material on algae. Comparison of oil yield of different plants compared to algae.	USA
http://www.algalbiomass.org/	Organisation facilitating commercialisation and market development of microalgae biomass (biofuels production and greenhouse gas abatement); deliver information to the public; networking.	USA
http://www.americanenergyindependence.com/home.aspx	This site is an independent publisher of reports, film documentaries, commentary, articles and current news of America's journey to energy independence. It offers a wide range of information on renewable energy sources including a section concerning algae.	USA
http://www.biocentricenergy.com/	Company web site with comprehensive information concerning algae as an energy source; offers also information on omega-3 fatty acids	USA
http://www.bpe.wur.nl/UK/Research/Projects/	Projects of the BioProcess Engineering Group of Wageningen University	Netherlands
http://www.eaba-association.eu/	Web site of the European Algae Biomass Association: lobbying for biomass and algae with links to EU regulations.	EU – located in Belgium
http://www.graskraft-reitbach.at/	Web Site of an agricultural cooperative society in Austria producing biogas from grass; the site offers information about biogas generation including a video and comprehensive biogas theory.	Austria
http://www.ieabioenergy.com/	IEA Bioenergy – International collaboration in Bioenergy. The research fields are structured in so called tasks working on different Bioenergy topics.	New Zealand
http://www.iea-biogas.net/	IEA Biogas Task 37 – Energy from Biogas and Landfill Gas	EU – located in Switzerland
http://www.nationalalgaeassociation.com/	Web site offering links concerning biofuels including event calendar and linking to conferences	USA
http://www.nrel.gov/biomass/	Web site by NREL: National Renewable Energy Laboratory offering technologic and research information on biomass topics including handouts from "Workshop on Algal Oil for Jet Fuel	USA

	Production" (February 2008)	
http://www.oilgae.com/	Information portal for researchers, companies and students	USA, India
http://www.originoil.com/	Site of commercial company working on oil extraction of algae	USA
http://www.solixbiofuels.com/	Commercial company listed on the stock exchange producing biodiesel and algae based by-products	USA
http://www.svlele.com/algae.htm	Web site of Indian Green Energy Awareness Center, Satish Lele. The site offers a comprehensive algae overview including an eBook (20 US$) by Dr. Smita Lele, University of Mumbai, Professor and Head of the Food Engineering and Technology Dept.	India

Annex 2 – List of Research Projects

Currently, various projects deal with research of the usage of algae as a renewable energy source. In most cases the focus is on algae oil as a base for liquid fuels. The following section introduces some impressing projects which are referenced at biomass related conferences and web sites in Europe and the USA.

NREL – Aquatic Species Program (ASP)

In the USA, the National Renewable Energy Laboratory (NREL), U.S. department of energy (DOE) carried out the so called Aquatic Species Program (ASP) from 1978 to 1996. The program involved dozens of universities and private companies to explore all aspects of algae technology. Within the program 3,000 strains of microalgae were screened. Additional research was done in an outdoor facility of 1,000 m^2 located in Roswell, NM. It could be observed that the strains produced an overall growth of 10 grams per square meter and day with peaks of 50 grams per square meter and day. One main goal of the project was to find out processes to produce biodiesel. Many process steps concerning algae cultivation, harvesting technologies and fuel production which are mentioned in this paper have been investigated and refined. As a result numerous aspects of algae usage for energy purposes have been documented. In 1998 a program close-out report ("A Look Back at the U.S. Department of Energy's Aquatic Species Program: Biodiesel from Algae") has been published summarising the work by the ASP (Sheehan, et al., 1998). In 2007 Eric Jarvis, NREL, National Bioenergy Center, presented the program retrospectively ("ASP: Lessons Learned") at the AFOSR Workshop in Washington D.C. There he states about the ASP that it "did not invent the concept of fuels from algae". Nevertheless, Jarvis thinks that it "could take the concept to a next level" (Jarvis, 2008). Publications related to biomass research web site of NREL can be found at http://www.nrel.gov/biomass/publications.html. Publications of 2008 regarding a workshop on "Algal Oil for Jet Fuel Production" can be found at http://www.nrel.gov/biomass/algal_oil_workshop.html.

Oilgae

Oilgae (www.oilgae.com) is an online portal for algae energy. It offers various publications – one of them is cited within this paper (Oilgae.com, 2010). Beside a frequently published newsletter the site offers many data on algae research at a global base and lists the projects which concentrate on fuel production (http://www.oilgae.com/b/cat/algae_fuel_research.html) in a blog; waste water and sewage treatment is also covered.

SBAE-Industries

SBAE Industries (http://www.sbae-industries.com/index.html) is a privately owned company working in the field of algae engineering and applied science. It exists since 2006 and cooperates with big European cleantech investment funds. The company and its projects were introduced during the IEA Bioenergy Workshop 11 "Algae – the Future for Bioenergy?" in Liege, Belgium on October 1, 2009 (Van Aken, 2009). The company concentrates on diatoms growing on carriers (see Figure 22: Diatoms growing on carriers). In this case algae remain fixed on carrying materials while water circulates through the system. This simplifies the harvesting of the fast growing diatoms on the one hand and needs less water on the other hand. The research offers an interesting alternative to traditional growing techniques, namely open pond systems and closed system photobioreactors. The aim of the company is to build so called *diatom fuel farms* using ocean water and non agriculture lands.

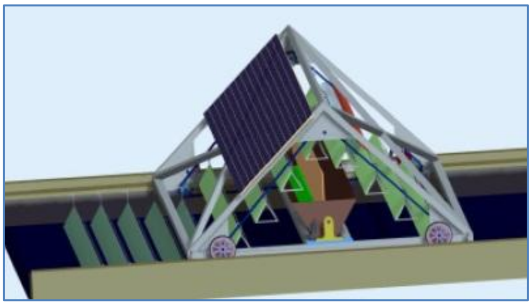


Figure 22: Diatoms growing on carriers (Van Aken, 2009)

Solix – Algae to Energy

The stock listed company "Solix – Algae to Energy" (http://www.solixbiofuels.com/) is situated in Colorado, USA. It produces algae for various purposes. It is listed here because it has developed a unique photobioreactor which combines open pond technology with closed photobioreactor technology. The tubes of the PBR are placed horizontally in water filled ponds in order to avoid overheating of the algae culture within the flexible tubes. This project shows that algae technology can be optimised by simple combination of published contents. The following figure describes conversion paths of algal biomass as applied by Solix.

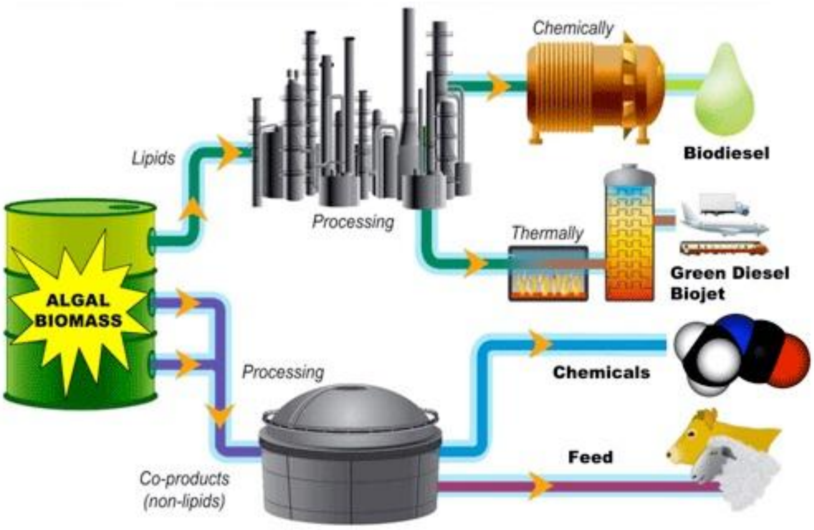


Figure 23: Conversion paths at Solix biofuels
(Solix Biofuels, 2009)

Wageningen UR

Information provided by Wageningen University (Wageningen, The Netherlands, http://www.wur.nl/UK/) has been cited several times in this work. The university also lists research projects which are currently running in the BioProcess Engineering group on the web. http://www.bpe.wur.nl/UK/Research/Projects/ (current as of August 5, 2010) lists over twenty algae related projects including a one page description of each project: Photobioreactors, harvesting methods, biofuels from algae etc. are itemised.

Annex 3 – Common Culture Collections with Culture Medium Recipes

When growing algae it is essential to provide the optimal environment for the species containing the appropriate amounts of needed nutrients. During the last decades numerous culture medium recipes have been documented by researchers. The following table lists common culture collections. More details can be found at http://wdcm.nig.ac.jp/hpcc.html (Andersen, 2005).

Table 33: Culture medium recipes on the Internet
(Andersen, 2005), with updates

Culture Collection	Internet Web Site URL
CCAP	www.ife.ac.uk/ccap/
CCMP	ccmp.bigelow.org/
NIES	www.nies.go.jp/biology/mcc/home.htm
PCC	www.pasteur.fr/recherche/banques/PCC/
SAG	www.epsag.uni-goettingen.de/cgi-bin/epsag/website/cgi/show_page.cgi?kuerzel=about
UTCC	www.biologybrowser.org/node/1156993
UTEX	www.utex.org

Annex 4 – Creating an Open Pond in Lower Austria

According to a phone speech with local authorities of Lower Austria (i.e. Central Administration, district Melk) from June 30, 2010 and based on the information published on the web pages of the local government the following data hast to be provided by project developers to get the necessary permissions for the project (Amt der NÖ Landesregierung, 2010), (Amt der NÖ Landesregierung, 2007). The project related information concerning the planned infrastructure of the algae culture (i.e. the pond system) has to be collected and should be sent to the authorities in an informal letter due to a general notification requirement; in addition, the pros and cons of the project should be described. It is important to depict the water source for the ponds. Furthermore, the letter of application should contain information about the ponds themselves, especially regarding a possible contact of the aquaculture with the ground water system. It is essential if portions of the ponds' water content will be released to the surrounding nature via an overflow system. If this is the case the expected composition of the overflow water has to be described. The following citation gives some details concerning the allowances for a pond system. The data is taken from the web site of the government of Lower Austria, Austria.

Allowance Proceedings

Beside a notification requirement there is no general need for an allowance to realize a project in the area of water bodies. The authorities decide about the allowance based on the informal information mentioned above. If it is decided that an allowance proceeding has to be completed before giving the allowance to the project developers the process is based on the laws pertaining to water and water ways. In this case an approval certificate has to be provided by the project team. The main influence factors for a mandatory allowance proceeding are:

- Usage of rivers, streams or lakes for the supply of operational equipments with water
- Usage of ground water as a water supply for pond systems
- Buildings near riverbanks or within flood areas of rivers and streams
- Projects influencing nearby bodies of water or the ground water including seepage of water containing nutrients and the change of temperature of the adjacent water systems

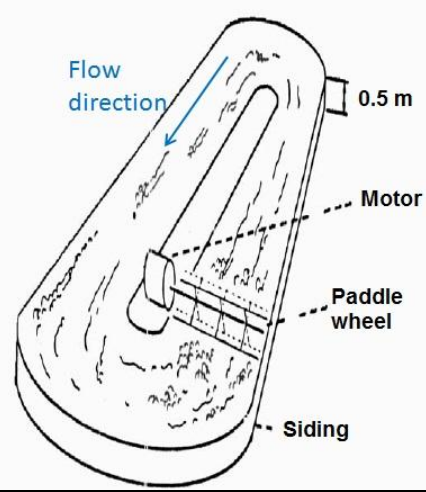
When using a river for the water supply of the pond system it is important not to exceed certain amounts of water. The limit is the so called Q_{347} value which is a statistically determined minimum amount of water within the river which is not under-run for at least 347 days per year.

Annex 5 – Algae Ponds by NREL: Guide for Large Scale Open Algae Ponds

At the NREL Workshop "Workshop on Algal Oil for Jet Fuel Production" which took place in February 2008 Ami Ben-Amotz from *The National Institute of Oceanography* of Israel presented results from his research concerning large scale algae ponds (Ben-Amotz, 2008). Following the publication the key issues regarding open pond system are listed in the following table.

Table 34: Design issues regarding open pond systems
(Ben-Amotz, 2008), adapted

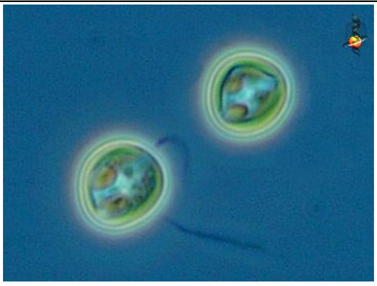
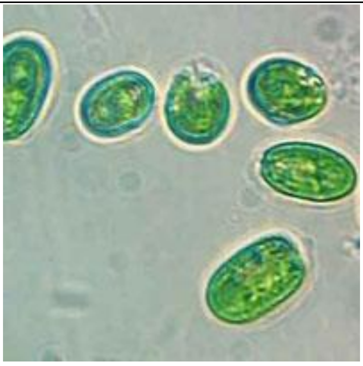
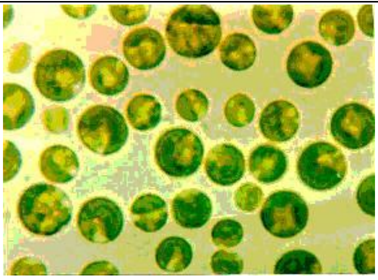
Topic	Details
Location	Same like higher plants. 25 years ago a different opinion was published: According to Benemann climatic regions with annual average temperatures of 15 °C and higher are optimal: 4 – 10 °C at night, 10 – 22 °C during days.
Area layout	As available, preferred lower temperatures
Ground preparation and pond lining	There are different options concerning the ground material of a pond: clay, asphalt, PVC or PE. Different materials show different durability, UV resistance and flow resistance. PVC and PE are easy to maintain, durable and cheap.
Outside walls and channel dividers	Possible materials for the outside walls and dividers are concrete and bricks; the cheapest material wins.
Pond depth	5 – 100 cm; the minimum is possible in large plants
Flow velocity	Typical values are 30 cm/sec
Optimal size area	There are different classes of open pond systems starting with 200 – 300 litres (micro bioreactor) up to 200,000 – 1.2 million

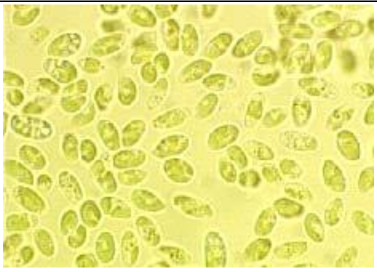
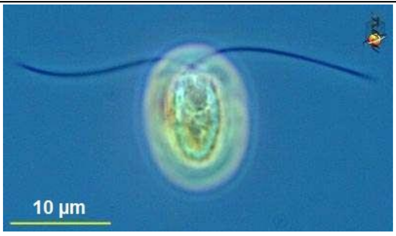
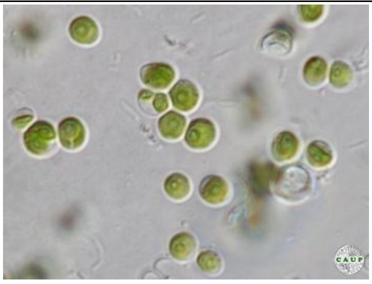
	litres (process bioreactor); the measurements range between 10 – 300 meters of length and 1 – 20 meters of width. Optimal commercial size areas go from 300 – 4,000 m²; larger area ponds are realised by stacking standard size ponds. Typical dimensions (w*n*l) w... width of lane; n... number of lanes per pond, l... length of pond: - 10 m*2*170 m = 3.400 m² (formerly used in the USA) - 10 m*2*150 m = 3.000 m² (formerly used in Israel) - 5 m*4*150 m = 3.000 m² Dimensioning: one paddle per 1.500 m² of water area.
Oblong raceways	Oblong ellipsoid raceways enable a steady water flow: common dimensions: 5 m * 150 m 
Distal end hydraulic radius	For an optimised water flow the radius of the pond end which has more distance to the paddle is essential. Asymmetric shapes (smaller after turn when seen in flow direction) are better than symmetric shapes.
Paddle wheels	Paddle wheels work as "inefficient" pumps; topics to consider are: rotation speed (mostly 5 – 30 rpm), number and design of blades, diameter (30 cm to 120 cm), immersion and angle relative to the water, material (stainless steel, fibreglass, marine plywood) positioning and location within raceway, motor and gear, maintenance.
Liquid flow, turbulence and mixing	In order to provide a homogenous culture consistence it is necessary to maintain turbulence within the water – this is done by the paddle.
Carbonation and pH	The theoretical use is about 2 grams CO_2 per gram algae biomass. Existing ponds use carbonation chambers (i.e. spots with a higher water level) where carbon dioxide is bubbled in at pH 7 – 8.
Site control and pH control	There are several process parameters which have to be monitored and controlled by a pond control system (PC). Technical parameters (paddles, pumps, gases, sensors, liquids) Aqua culture biological parameters (pH, flow, water depth and temperature, CO_2, nutrients concentration etc.)
Pond accessories	Additional equipment includes machinery to clean the ground infrastructure from time to time

Annex 6 – Pictures of Algae

The following section shows some of the algae species mentioned in this paper in pictures. The pictures may show the fascinating world of algae.

Table 35: Pictures of algae – various sources

Picture	Details	Source
 Picture 7: Spirogyra species (size: 10 – 40 µm)	Fresh water algae	http://protist.i.hosei.ac.jp/PDB/images/Chlorophyta/Spirogyra/group_D/sp_05.jpg June 13, 2010 Referenced at 3.1.4.1.2, 3.1.4.3
 Picture 8: Pavlova lutheri (diameter: 4 µm)	Marine phytoplankton	http://www.ncbi.nlm.nih.gov/genomeprj/12699/ June 13, 2010 Referenced at 3.1.4.3
 Picture 9: Tetraselmis suecica	Marine algae	http://www.nc3rs.org.uk/downloaddoc.asp?id=747 June 13, 2010 Referenced at 3.1.4.1.1, 3.1.4.3
 Picture 10: Chlorella pyrenoidosa (diameter: 2 – 8 µm)	Fresh water algae	http://www.theherbprof.com/hrbchlorella.htm June 13, 2010 Referenced at 3.1.4.3

 Picture 11: Monodus subterraneus (cell size approx. 5 µm)	Fresh water algae	http://www.ppo.be/P/content.php?Class=energy&ID=6 June 26, 2010 Referenced at 3.1.4.3, 3.1.5
 Picture 12: Dunaliella tertiolecta (cell size: approx. 10 µm)	Marine algae	http://www.eol.org/pages/4472 August 1, 2010 Referenced at 3.1.2.3.1.5
 Picture 13: Chlorella sorokiniana (cell size: 2 – 10 µm)	Fresh water algae	http://botany.natur.cuni.cz/algo/caup-list.html August 1, 2010 Referenced at 3.1.2.3.1.5
 Picture 14: Euglena gracilis (cell size: diameter: 10-23 µm, length: up to 60 µm)	Fresh water algae	http://botany.natur.cuni.cz/algo/caup-list.html August 1, 2010 Referenced at 3.1.2.2, 3.1.4.1, 3.1.4.1.2, 3.1.4.3
 Picture 15: Algae community		http://www.sbae-industries.com/Technology/specs/algal_community.html August 5, 2010