· U C ·

FCTUC FACULDADE DE CIÊNCIAS
E TECNOLOGIA
UNIVERSIDADE DE COIMBRA

Rodrigo da Costa Miguel

COST ANALYSIS OF BIOMASS GENERATION FROM MICROALGAE

2013-09-02

· U C ·

UNIVERSIDADE DE COIMBRA

Faculdade Ciências e Tecnologia da

Universidade de Coimbra

COST ANALYSIS OF BIOMASS GENERATION FROM MICROALGAE

Data Sheet:

Type of work	**Thesis for MSc**
Title	**Cost Analysis of Biomass Generation from Microalgae**
Author	**Rodrigo da Costa Miguel**
Advisors	**Prof. Dra. Patricia Carla Gama Pinto Pereira Silva Vasconcelos Correia** **Prof. Dr. Fausto Miguel Cereja Seixas Freire**
President of the Jury	**Prof. Dr. Luís Miguel Cândido Dias**
Examiner	**Prof. Dr. Pedro Manuel Tavares Lopes de Andrade Saraiva**
Course identity	**Energy for Sustainability**
Scientific Area	**Science**
Path	**Energy Systems and Energy Policies**
Data	**2013**

Acknowledgements

First, I would like to thank my thesis supervisors, Patricia Pereira Silva and Fausto Freire, for steadfast support during the entire thesis process. I appreciate the patience, guidance, encouragement and advice provided throughout the writing process. Thank you for your valuable suggestions and criticisms. Furthermore I would like to thank, Lauro Ribeiro for introducing me to the topic as well for the support on the way.

This work has been framed under the Initiative Energy for Sustainability of the University of Coimbra and supported by the Energy and Mobility for Sustainable Regions - EMSURE - Project (CENTRO-07-0224-FEDER-002004). The support from Portuguese Science and Technology Foundation (FCT) projects MIT/SET/0014/2009 and PTDC/SEN-TRA/117251/2010 is also acknowledge.

I cannot find the words to express my gratitude to the Energy for Sustainability initiative for the opportunity and the environment to cultivate my interest in the energy field.

This thesis would not have been possible without my family that has given me the opportunity to receive an education from the best institutions and provided support throughout my life. Last, I would like to thank my friends for their encouragement and support, especially you for the patience, understanding, and guidance. Your wisdom has helped me immensely throughout this process.

Resumo

As microalgas caracterizam um grupo grande e diversificado de organismos fotossintéticos. Presentemente, o cultivo de microalgas é tido como uma opção viável em lagoas e fotobiorreatores fechados. Embora os fotobiorreatores possam possuir certos benefícios, o seu custo pode revelar um enorme impedimento para um desenvolvimento em larga-escala. As microalgas apresentam um desenvolvimento rápido, precisando apenas para o seu crescimento de, água, luz solar, dióxido de carbono (CO_2) e alguns nutrientes adicionais. Neste trabalho, o custo de produção assumido para os fotobiorreatores foi aproximadamente 24€/kg biomassa seca. Durante a análise de custo, foi possível identificar que os custos relativos à mão-de-obra, logo seguidos dos encargos com depreciações, correspondem aos elementos com maior dimensão na estrutura de custos final. A metodologia de análise de cenários foi aplicada para avaliar o nível de custos de um sistema de produção em larga escala. Foi possível identificar uma possível redução de custo de aproximadamente de 16 €/kg, obtendo um preço final de biomassa de, aproximadamente, 7,70 €/kg. Para o cenário de média escala, o preço final aproximado de biomassa foi de 14 €/kg. Através de um cenário em que se adoptaram diferentes níveis de produtividade, foi possível demonstrar que para um "cenário produtividade máxima", a redução é excecionalmente elevada, evidenciando-se valores próximos dos 5,25 €/kg. Já quando consideramos um "cenário de alta produtividade", o valor cai para cerca de 10,50€/kg.

Palavras-chave: Microalgas, fotobiorreatores, Custo produção, Trabalho

Abstract

Microalgae represent a large and diverse group of photosynthetic organisms. The cultivation of microalgae is currently feasible in ponds raceway (open system) and closed photo-bioreactors. Microalgae are characterized by rapid growth. The only elements that they need to grow are water, sunlight, carbon dioxide (CO_2) emissions and some nutrients. This work performs a cost analysis for the production of biomass. The production cost for the Photobioreactors system was about 24 €/kg of dry biomass with labor and depreciation representing the major elements contributing to the final production cost of the microalgae biomass. Three different scenarios of microalgae biomass cultivation with different volumes were evaluate, for the large scale production system, a cost reduction of 16 €/kg is possible to achieve, with a final price of biomass of approximately, 7.70 €/kg. For the medium scale scenario, the final price of microalgae biomass was 14 €/kg. A further significant scenario is the possibility of assuming different productivities, for a "maximum productivity scenario", the reduction is exceptionally high, to values close to 5.25 €/kg, for the "high productivity scenario" the value decreases to 10.50 €/kg.

Keywords Microalgae, Photo-bioreactors, Production Cost, Labor,

Table of contents

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

€ - Euro

ASP - Aquatic Species Program

C – Carbon

CH_4 – Methane

CO_2 – Carbon dioxide

DOE – United States Department of Energy

FCI – Fixed capital investment

g – Grams

GHG – Greenhouse gas

H2 – Hydrogen

IEA – International Energy Agency

kWh – kilowatt-hour

LCA – Life cycle assessment

m^2 – Square meters

MIT - Massachusetts Institute of Technology

N – Nitrogen

NER – Net energy ratio

NOx - Nitrogen oxides

NREL - National Renewable Energy Laboratory

PBR – Photo-bioreactor

R&D - Research and Development

SERI - Sustainable Europe Research Institute

SOx - Sulfur oxides

T – Metric Tonne

1. INTRODUCTION

In 1952, the Carnegie Institution of Washington published ‘Algal culture from laboratory to pilot plant' (Burlew, 1953), which summarized what had been done on large-scale algal culture before, during and shortly after World War II. In that article, experts predicted the great potential of algae as a product (Chaumont, 1993), with the production of Chlorella as food and energy source (Darzins et al., 2010).

1.1. Background

Microalgae were first mass cultured on a rooftop at Massachusetts Institute of Technology (MIT) during the early 1950s (John R Benemann, 2008), and received a big boost during the energy crisis of the 1970s, when projects were initiated to produce gaseous fuels such as; hydrogen (H_2) and methane (CH_4). From 1980 to 1996, the U.S. Department of Energy supported the Aquatic Species Program (ASP), a relatively small effort (about $25 million over almost 20 years) with the specific target of producing oil from microalgae (Sheehan et al., 1998). The ASP program supported many research projects, which included both researchers at the Sustainable Europe Research Institute (SERI), the National Renewable Energy Laboratory (NREL) and many cooperating universities, research institutes and small companies.

Microalgae culture is one of the contemporary biotechnologies and includes the use of microalgae through mass cultivation and conversion of the harvested biomass into a variety of additional valuable products (Bumbak et al., 2011; Pulz & Gross, 2004). Recently, driven by the crisis of biotechnology, microalgae started to be seen as a potential alternative solution to many current problems in various sectors (Surendhiran & Vijay, 2012). The cultivation of microalgae for obtaining biomass and its products is a synthesis of established industrial activity on a commercial scale in certain countries and with production is carried out by large companies. According to Spolaore et al., (2006), the microalgae biomass industry currently produces more than 5,000 tons of dry biomass per year, generating income of more than $ 1.25 billion dollars per year, not including by-products, which demonstrates the potential for exploitation of this specific industry.

Microalgae biomass it is used for broad range of solutions depending on the microalgae strain and the cultivation conditions (Surendhiran & Vijay, 2012). There are diverse applications ranging from the production of biofuels to the production of pharmaceuticals, cosmetics, aquaculture, food and animal feeds (Batista et al., 2008; Priyadarshani & Rath, 2012). They are also known for their ability to remediate effluents, such as industrially generated carbon dioxide ($CO_{2)}$ and inorganic nutrients contained in industrial / agricultural / municipal waste waters (McGinn et al., 2011). Since the late 1970’s, researchers have observed algae as an optimal feedstock for biofuels production since it would not compete with food production and because it has the ability to use concentrated CO_2 from industrial sources i.e., smokestacks (Collet et al., 2009).

Algae is also seen as attractive since some algal species can achieve oil concentrations as high as 80% on a dry weight basis (Spolaore et al., 2006), consequently delivering fixed carbon in a form more readily processed than ligno-cellulose biomass. Microalgae species as feedstock for biofuels have gained extensive interest. They can be produced in areas inappropriate for crops, and can potentially grow at a much faster rate (Schenk et al., 2008; Sheehan et al., 1998). Chisti (2007) reports a 15 – 300 times higher oil yield from microalgae compared to traditional land based crops like rapeseed and palm oil. Figure 1 illustrates the biodiesel production rate of different biomass sources. It is possible to observe that algae have by far the highest production rate.

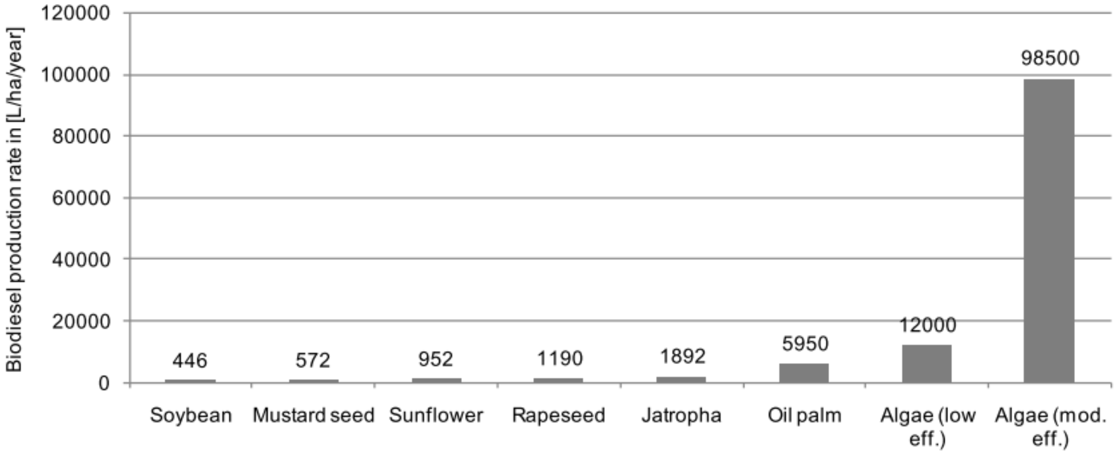


Figure 1 Biodiesel yields for different biomass sources; Algae (low efficiency) based on algae growth rate of 10 g/m2/day and 30 % Triacylglyceride1 (TAG); Algae (moderate efficiency) based on algae growth rate of 50 g/m2/day and 30 % TAG; Real, current algae cultivation systems are within the low and mod. Algae

growth rate range, e.g. Seambiotic Israel (20 g/m2/day and 8 - 40 % TAG), HR BioPetroleum Hawaii (50 g/m2/day and 30 % TAG); Data taken from (Schenk et al. 2008).

Regardless of the tremendous potential of algae feedstock's to replace significant quantities of petroleum-based fuels, the algae biofuels industry is still in its infancy (Becker, 2006). At the moment, there is limited pilot scale production which all started operating recently. Biodiesel from algae is being copiously researched, as governments and scientists search urgently for an environmental and economically sustainable fuel (Wolkers et al., 2011; Singh & Gu, 2010).

1.2. Definition of the problem

The overall commercial viability and implementation of a microalgae biomass production system will depend on economic factors. Regardless of what advances could be developed in terms of scientific breakthroughs, the fact remains that the commercial development will not adjust their funding capital on intensive projects unless the risk-return ratio is acceptable to the investors. In an attempt to find the solutions to these general questions, this thesis includes a case study developed based on a certain number of assumptions. The case study includes a cost analysis for producing algae biomass with a photo bioreactor system and several scenarios comparing different solutions and alternatives within the production system itself.

For this study, a set of case-specific research assignments were formulated:

1. What is the current status and potential of microalgae? There is a state-of-the-art review based on economic assessments.
2. What are the costs of producing dry algal biomass in a tubular bioreactor?
3. What are the key factors for minimizing the cost of production?

The study will be done based on the relationship between inputs and outputs for the economic evaluation. The following chapter presents the goals of the dissertation. This is followed by methodology in Chapter 3, which sets the applied methods and structure of the work focused on answering the research questions listed in the section above. Chapter 4 summarizes the results of the case study and scenarios as well as assesses their main insights.

1.3. Goals

The challenge when looking at a new technology, such as biomass production from microalgae, is a lack of clear public information. Nevertheless, applying economic tools and analyses help to derive a better understanding of the potential behind microalgae. This research has the objective of combining literature with economic analysis. This dissertation will consist of two parts. The first part is focused on topics concerning technology with a broad literature review. The second part will focus on an economic analysis of producing algae biomass, consisting of the development of a particular case study.

Economic analysis is a strong tool that can be used to both evaluate the production cost of algae biomass production and help to identify the key factors contributing to the production cost. The purpose of this dissertation is to provide a literature review of the relevant variables needed for an economic analysis and to develop an estimate of the costs of producing algae biomass for the microalgae industry based on the relevant assumptions and data.

The main goal of this dissertation is not to produce a final cost estimate currently there are too many uncertainties to allow this – but to give a source to examine the configuration of the economics for different scenarios of production. Secondary goals of this thesis is to make available useful information for public and industry decision makers as they consider their investment and support their key decisions for the implementation of a microalgae biomass production system and to evaluate the economics in order to better understand the current status of algae biomass technology production.

1.4. Methodology

The following sections will outline the structure of the dissertation, and describe the underlying methodology of the methods used in the case study. In order to perform a comprehensive case study, an extensive amount of data must be gathered. These data include process parameters, economic data and knowledge about the technical system where the process operates. In this work, these data have been gathered from state-of-the-art reports and scientific articles regarding the production of algae biomass.

1.4.1. Literature review – building knowledge

In order to complete a comprehensive case study, an extensive amount of data must be collected. These data include process factors, economic data and knowledge about the technical system where the process operates. The first section centers on the description of microalgae technology potential and current status, covering algal biology, cultivation, harvest, extraction and conversion to liquid bio-fuels. The second section of the dissertation consists of a broad review of all the literature surrounding the most relevant economic assessment.

1.4.2. Theoretical and analytical framework

The second part outlines a cost analysis for the production of microalgae biomass from specific technology. It includes a comprehensive investigation based on a certain number of assumptions. A Microsoft Excel model of the process was developed in order to create a tool for analyzing the whole algae cultivation process based on the data collected from the literature. Capital and operating costs were estimated based on literature studies, and standard engineering calculations. During the thesis, scenario analyses were performed considering alternative possible outcomes. Chapter 4.2 details microalgae biomass production scenarios for productivity scale, volume scale and certain assumptions within the system (CO_2, water and nutrients).

1.4.3. Investment cost estimation methods

The investment cost estimation methods can be divided into three main groups (Zugarramurdi et al., 1995):

1. Universal methods: determine investment costs as one value and therefore allow a very rough estimate (Kerdoncuff, 2008). Total fixed capital can be calculated from the current sale price of the product and annual capacity of the plant (Woods, 1975). This method is applied if data is available only for other comparable production facilities. The estimation error is at about 40 percent.
2. Lang factor: This factorial approach was first suggested by Lang in 1948. This method is used to estimate the order of magnitude of investment. It establishes that the costs of an industrial plant can be obtained by multiplying the costs of the basic equipment by a factor. These factors, known as 'Lang factors" are characteristic of the industry sector considered, particularly the type of products manufactured, the average cost of equipment items used, plant capacity and location (Lang, 1948). The estimation error is between 10 and 15 percent (Jelen & Black, 1983; Kerdoncuff 2008)
3. A detailed estimation of investment costs: A detailed estimation of investment costs requires a direct estimation of each investment position. Therefore, a detailed plan on the materials used, spatial plant set- up and further specification are needed. This is the most time consuming and information demanding method. (Gerrard, 2000). The estimation error for this method is up to five percent (Emhjellen & Osmundsen, 2002).

The methods primarily differ in terms of the data requirements as well as the time and financial resources consumed. The option for the cost methodology model chosen was the Lang factor, because it is possible to identify the approximate cost of major equipment. An important topic is the accuracy of the data inputs. One important limitation in applying this particular case is the limited access to data. The accuracy of the estimate will vary depending on the level of detail known about the design of the microalgae biomass production plant.

1.4.4. Capacitive adjustments

In our case study, cost data from the former study was used and adjustments were necessary. Following this routine, to determine the cost of generating microalgae biomass at any other scale, it is necessary to modify the cost of the major equipment according to the scale factor. Equation (1) characterizes the economies of scale because purchasing a piece of equipment with twice the capacity is less than twice as expensive (when the exponent is less than 1.0). If, for a specific piece of equipment, this exponent is larger than 1.0, the most cost-effective way of scaling up is to duplicate the equipment.

The cost of a process or equipment can be scaled up or down from a basic size by using an exponential law for which a value varies between 0.3 and a maximum scale-up factor of 1. For our study, an exponential scaling factor for the ratio of capacities of 0.85 is chosen. (Acién et al., 2012).

$$\mathrm{CostB} = \mathrm{CostA}\left(\frac{\mathrm{SizeB}}{\mathrm{SizeA}}\right)^{0.85}$$

Equation 1: Scaling of equipment

The major equipment for the PBR system will be scalable based on the chosen size of the facility. For the model to be scalable, it will be based on a general facility design, which resulted from a mixture of the literature, research and own calculations. The scaling up of the model will allow it to automatically recalculate fixed costs. A certain number of specific costs aren’t easy to estimate. They are primarily estimated based on the origin of the purchased equipment cost or the fixed capital investment (FCI) since there is no correlation between them. It is possible to take as an example the raw materials and utilities. Those expenses are estimated from the mass and energy balances (e.g. raw materials demand, utilities) (Ereev & Patel, 2011).

If producers and consumers of a technology increase experience, the costs for manufacturing and usage drop. The relationship established is expressed in Equation 2 with the production costs of the first unit produced C_0, the cumulative production A, the costs per unit after producing A units of a product C_{cum} and the experience index b.

$$C_{cum} == C_0 * A^{-\,b}$$

Equation 2: Experience curve

The progress ratio indicates at which rate the costs per unit will decrease if production is doubled (Pienkos & Darzins, 2009).

2. ALGAE RESOURCES – STATE-OF-THE-ART-

This section gives an overview of algae, details the positive attributes of producing algae biomass and describes the process of growing, harvesting and production of biomass. This chapter also aims to provide a literature review of the relevant economic assessments. This is not exhaustive. The purpose is to provide a foundation to propose an economic analysis.

2.1. Organism overview

Chisti 2007, states that microalgae are " sunlight-driven organisms that have the capacity to convert CO_2 to potential bio-fuels, foods, feeds and high-value bioactive" (pag. 95) . They are very effective since they use the available light to transform inorganic compounds into simple sugars. Algae are defined as any organisms which are plant like and perform photosynthesis. Based on their morphology and size, algae are typically subdivided into two major categories macro-algae and micro-algae (Singh et al., 2011). Further use of the word algae in this report refers to the group of microalgae.

A single algae organism is formed by a mixture of lipids, carbohydrates, proteins and hydrocarbons. Every strain of algae varies by the composition of these elements. It is possible to find approximately 1,000 species of algae presenting potential for the production of biofuels (Renaud & Stroud, 2011).

As a source of biomass, potential advantages of algae include:

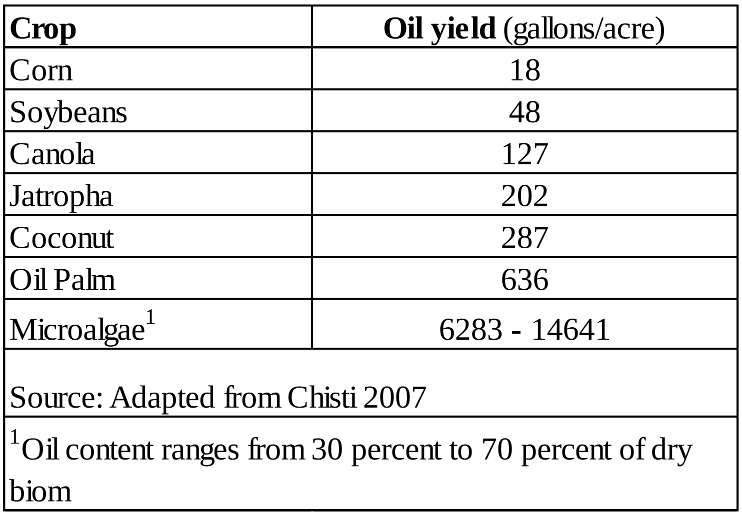
- the ability to grow in fresh, salt and waste water (Schenk et al., 2008);
- the capacity to produce non-toxic and biodegradable biofuels as well as high concentrations of commercially valuable compounds such as proteins, carbohydrates, lipids and pigments (Schenk et al., 2008);
- the ability to be used with wastewater treatment (Christenson & Sims, 2011);
- the opportunity for cultivation on infertile desert land, thus reducing competition for agricultural land (Pienkos & Darzins, 2009).

2.2. Productivity and lipid content

The two main interests for increasing efficiency of algae production are high productivity, or biomass accumulation, matched with a high lipid content of that biomass (Christenson & Sims, 2011). Lipid contents usually refers to the oil extracted from algae biomass which is then refined into the final liquid fuel product. Lipid levels are normally found at between 20 to 75% of total biomass dry weight (Singh & Gu, 2010) but are usually calculated at between 25 to 40% of dry biomass (Huntley & Redalje, 2006; Sun et al., 2011).

In terms of evaluations of the biomass algae potential with other terrestrial food crops, biomass originally from microalgae can grow faster when compared with terrestrial crops, which take a season to grow and only contain a maximum of about 5 percent dry weight of oil. Microalgae grow quickly and contain high oil content (Chisti, 2007). This is why microalgae are the focus in the algae-to-bio-fuel arena. Table 1 presents the list of the potential yields of oil produced by a different number of crops and compares these values to oil yields from an open pond growing microalgae (Davis et al., 2011a; Fehrenbacker, 2012).

Table 1 Oil yields (Chisti, 2007)



Crop	**Oil yield** (gallons/acre)
Corn	18
Soybeans	48
Canola	127
Jatropha	202
Coconut	287
Oil Palm	636
Microalgae[1]	6283 - 14641
Source: Adapted from Chisti 2007	
[1]Oil content ranges from 30 percent to 70 percent of dry biom	

When compared with other crops used for the production of other bio-fuels, microalgae is expected to play a key role in the future of the transportation sector.

2.3. Resulting end product

Algae biomass can be processed into different types of end products. Strains of algae can be prepared to produce a variety of lipids, hydrocarbons and other complex oils (Figure 2 gives the extensive cell content of these major fractions, their elemental composition and energetic properties) (Rösch et al., 2009; Williams & Laurens, 2010). By-products, which can influence the economic potential for producing algae biomass, are also considered. Biodiesel is a fuel derived from algae that has received more attention due to its potential to replace dependence on fossil fuels, mainly in the field of transport (Dinh et al., 2009).

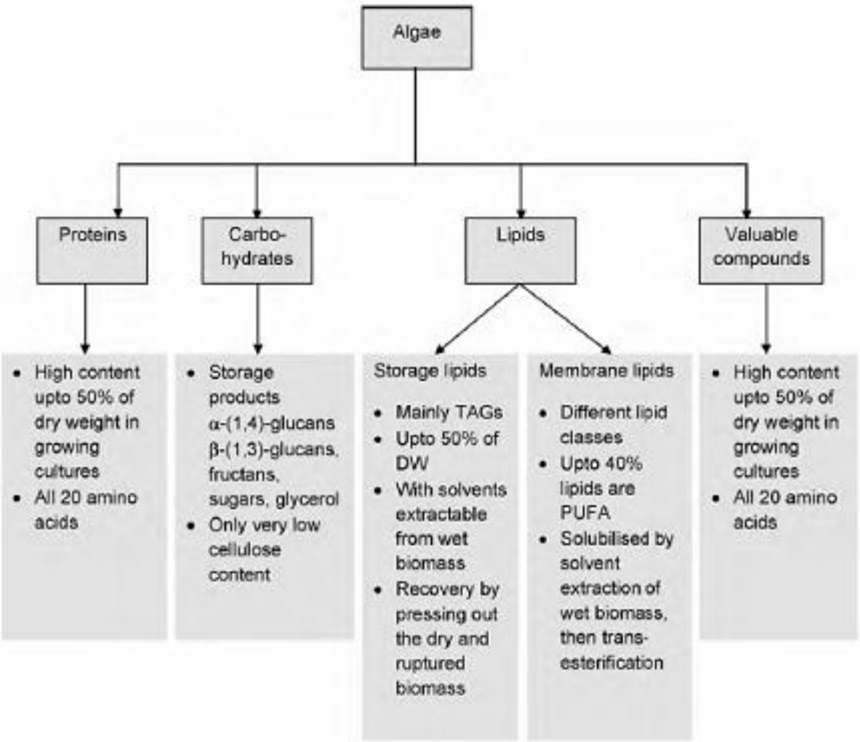


Figure 2 Overview of components of microalgae and potential end products (Singh & Gu, 2010)

Biodiesel and flue gas are the main approaches, but bio-ethanol, bio-methane, and bio-hydrogen are also important end products that can be derived from algae (Singh & Dhar, 2011). The process of extracting lipids from microalgae is one of the more costly and debated processes involved in biodiesel production from this feedstock. This process can determine the overall sustainability of processing biodiesel from microalgae. Microalgae can be used to produce a wide range of metabolites (Table 2), such as proteins, lipids, carbohydrates, carotenoids or vitamins for health, food and feed additives, cosmetics and for energy production (Araujo et al., 2011; Becker, 2006)

Haematococcus pluvialis is an important example. It is the organism with the highest natural content of astaxanthin, which is taken up by fish via the marine food chain. Astaxanthin is used as a pigment in aquaculture in order to enhance the pink color of shrimp, salmon and trout meat as well as in cosmetics. Because of its anti-oxidative potential and beneficial properties for both the cardio- vascular system and human eye function, it is also used as a dietary supplement (Fraunhofer, 2011).

Table 2 List of useful substance contained in algae

Useful substances contained in algae	
Pigments / Carotinoids	β-carotene, astaxanthin, lutein, zeaxanthin, canthaxanthin, chlorophyll, phycocyanin, phycoerythrin, fucoxanthin
Polyunsaturated fatty acids (PUFAs)	DHA (C22:6), EPA (C20:5), ARA (C20:4), GAL (C18:3)
Antioxidants	catalases, polyphenols, superoxid dismutase, tocopherols
Vitamins	A, B1, B6, B12, C, E, biotin, riboflavin, nicotinic acid, pantothenate, folic acid
Other	antifungal, antimicrobial and antiviral agents, toxins, amino acids, proteins, sterols, MAAs (Mycosporine-like Amino Acid (absorb UV)) for light protection

2.4. Growth system technologies

Apart from the focus on photoautotrophic biomass production in this study, heterotrophic and mixotrophic production exist (Brennan & Owende, 2010).

Brennan & Owende (2010) state that “under natural growth conditions, phototrophic microalgae absorb sunlight, and assimilate CO_2 from the air and nutrients from the aquatic habitats. Consequently, artificial production should attempt to replicate and enhance the optimum natural growth conditions” (p.4).

Algae must be grown on a “ large scale to have a huge substantial impact on biomass production” (Chen et al., 2010). Naturally occurring algae are very low in density. In order to get a significant increase in the productivity; it is necessary to find ways to increase the growth rate and density of algae in the culture media. Currently the only feasible methods for the large-scale production of microalgae include the use of open tank "raceway ponds" (Flickinger, 2009; Terry & Raymond, 1985) or closed tubular photo bioreactor technologies (PBR) (Chisti, 2007).

2.4.1. Photobioreactor systems (PBR)

All PBR are built in a similar manner: a man-made vessel holds the algal culture which is composed of water, nutrients, algae and CO_2. The design principle of a usual tubular PBR system is shown in Figure 3 (Kleivdal et al., 2012). PBR have been effectively used for producing large quantities of microalgae biomass (Carvalho et al., 2006; Chisti, 2007; Pulz, 2001). The PBR itself is used to stimulate biological growth by establishing a system control of the environmental parameters including light, by keeping the proper temperature and feeding in the optimal level of any additional nutrients (Kleivdal et al., 2012) . The tubes are made of acrylic and are designed to have light and dark intervals to enhance the growth rate. The solar collector is oriented to maximize the sun capture in the system (Molina Grima et al., 1999; Sánchez Mirón et al., 1999).

PBR can add additional CO_2 to the growth medium process which actually improves algae growth. This specific closed PBR system also guarantees optimal growth by protecting microalgae strains from predators, foreign bugs and other strains of microalgae that might result in a specific infesting strain. It also offers better control over a range of other growing conditions, like the pH, light, carbon dioxide, and temperature. (Bullis, 2012). PBR is still the one of the favorite current option for producing microalgae, for research & development (R&D) and many companies. PBR still can be more productive when compared to open ponds, and as a result requires less land, than open pond systems. However, the technical issues regarding their use and maintenance are difficult and demanding. One key drawback is the significantly higher capital costs than the raceway systems.

Figure 3 A commercial PBR set up at the NRC Institute for Marine Biosciences research station in Ketch Harbour, Nova Scotia (www.chempuretech.com).

The main problems found in the operations of PBR are the control of oxygen concentration (Weissman et al., 1988) and the overheating in summer which may require special and costly preventive measures (Torzillo et al., 1986). It is now possible to identify a variety of tubular photo-bioreactor designs, including flat plate annular or column PBR. Flat plate PBR has the main advantage of increasing the surface area of illumination and allows for a greater density of cells over a thin layer (Hu et al., 1996; Zhang et al., 2002; Hoekema et al., 2002). Column PBR offers better control and volumetric mass transfer rates, and is aerated from the bottom. Their performance is equal to or better than tubular PBR. Flat plate systems were the first one introduced, although column reactors are receiving currently receiving a lot of consideration, although both systems are still yet at the pilot scale (Brennan & Owende, 2010; Jorquera et al., 2010).

2.4.2. Raceway ponds

The "raceway ponds" have been used for the cultivation of microalgae since the 1950´s. “They are typically made of a closed loop (Figure 4), oval shaped recirculation channels (normally between 0.2 and 0.5m deep), with mixing and circulation required to stabilize algae growth and productivity" (Brennan & Owende, 2010, pag. 4). The paddlewheel is in continuous operation to prevent sedimentation. The microalgae CO_2 demand is commonly satisfied from the air present in the surface, although submerged aerators may be installed to enhance the CO_2 absorption (Chen et al., 2010; Chisti & Yan, 2011; Sanchez Miron et al., 2003).

The raceways usually require lower upfront capital costs than PBR and they are relatively less expensive to operate but they have the problem of lower productivity standards. Open ponds have many disadvantages (Benemann et al., 2011; Richmond, 1992). Large ponds display significant evaporative losses, less efficient use of CO_2, the absence of temperature control and low concentrations, sometimes even in much smaller volumes when compared with the PBR systems (Shelef & Sukenik, 1984). Ponds are also much more likely to face contamination by other species of microalgae, and by microorganisms which feed on the algae (Chisti, 2007; Davis et al., 2011b)

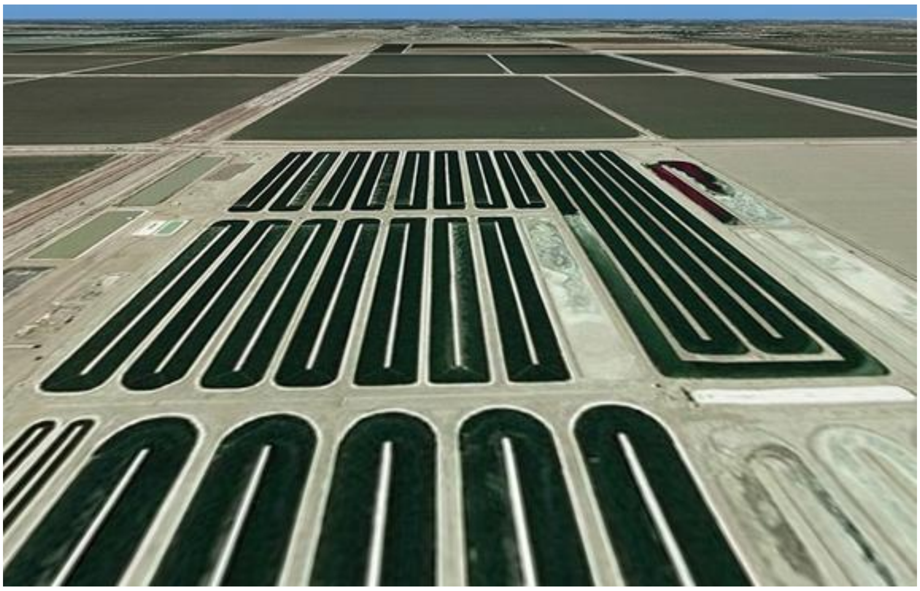


Figure 4 outdoor raceway ponds located in the Gulf Coast, the Southeastern seaboard (AlgaeIndustryMagazine.com)

2.5. Harvesting and extraction

One of the main difficulties with microalgae production is harvesting. After cultivation more than 99 wt-% of the algae/water mixture consists of water (Wiley et al., 2011). The lack of an economical and efficient method to harvest algal biomass is a major drawback in boosting its full-scale application (Greenwell et al., 2010). Current methods include biological methods as well as chemical, mechanical and electrical based operations (Singh & Olsen, 2011). Depending on the downstream processing option, the biomass harvested must be completely dry or the water fraction must be removed. Consequently, after recovery it will be necessary to have a final drying process. The harvesting and drying procedure can be highly energy intensive (Xu et al., 2011).

Drying of microalgae wet biomass is a main obstacle to industrial-scale processing of microalgae biomass (Sathish et al., 2012). The dilute nature of harvested microalgae cultures produces a huge operational cost during dewatering. Currently there is no superior method of dewatering microalgae (Sathish et al., 2012). The main harvesting techniques focusing on algae biomass are (Brennan & Owende, 2010; Grima et al., 2003; Schenk et al., 2008);

- Centrifugation
- Gravitational sedimentation
- Filtration
- Flocculation

Centrifugation is a fast and energy intensive harvesting option, which depends on the settling properties of the cells, culture residence time and settling depth (Molina Grima et al., 2003). The high harvesting efficiency is over 95 percent and comes at the cost of high energy consumption (Bosma et al., 2003; Heasman et al., 2000).

Gravitational sedimentation when compared to centrifugation is a slower process and requires less energy. The relevant settling properties are the cell diameter, the biomass density in the culture and the sedimentation velocity (Nurdogan & Oswald, 1996). The key disadvantages are that it involves more time and space than other harvesting methods (Schenk et al., 2008) as well as having limited applicability to large algae – a minimum cell size of 70 µm is essential (Muñoz & Guieysse, 2006).

Filtration is carried out normally on membranes of modified cellulose, with the aid of a suction pump. The main benefit of this method as a concentrating device is that it is able to collect microalgae or cells of very low density. However, concentration by filtration is insufficient for small volumes and leads to the subsequent clogging of the filter by the packed cells once a vacuum is applied (Schenk et al., 2008).

Flocculation is a method of separating algae from the medium by using chemicals to increase the potency of the algae in order to form lumps. Conventional flocculation applies inorganic chemicals as a flocculant (Schenk et al., 2008), whereas auto-flocculation functions by the change of environmental conditions to induce flocculation (C. Rösch et al., 2009). Both can be applied as a preliminary step to the other harvesting techniques listed above (Schenk et al., 2008).

2.6. Resource inputs to growth systems

For achieving a good ratio of cultivation, a microalgae system frequently requires a series of energy and environmentally explicit set of conditions, which change continuously depending on the category of strain used. These include requirements for light, temperature ranges, CO_2 concentration, nutrient composition, salinities and mixing conditions.

2.6.1. Photosynthetic efficiency

The mechanism of photosynthesis in microalgae can be compared to higher plants but they are generally more efficient converters of solar energy because of their simple cellular structure (Kirrolia et al., 2013). Photosynthetic efficiency is the fraction of light energy converted into chemical energy during photosynthesis in plants and algae (Clarke, 1995). Microalgae can conserve a maximum of 9–10% of the solar energy (photosynthetic efficiency) but microalgae outdoor production systems so-far rarely exceed 6% (Carvalho et al., 2006).

The quantity of light absorbed by an algae cell suspended in a PBR depends on numerous factors, including the precise position of the cell at a given instance, the density of the culture, and the pigmentation presented on the cells. Since algae cells grow in aqueous suspension; they have efficient access to water, CO_2, and other nutrients which represents an advantage compared to terrestrial crops (Spolaore et al., 2006; Walker et al., 2005; Widjaja et al.,2009).

2.6.2. Light

Light represents an important and vital factor that has the possibility of controlling the success and failure of biomass microalgae cultures. Controlling the intensity and availability of the sunlight is an important step in providing a clean and efficient source of light to the biomass.

According to Hannon et al., (2010) “light provides the energy for carbon fixation, and is converted to chemical energy through photosynthesis, providing the building blocks for bio-fuel production” (p. 10). Algae use light as a source of energy, algae growth rates are frequently limited by light diffusion into the ponds from both self-shading and light absorption by the water, and these restrictions are major determining factors of pond depth. (Dragone et al., 2010; Moheimani & Borowitzka, 2007).

2.6.3. Water and nutrients

Water is a key factor in which most of the productivity of algae biomass depends on. A regular and sustainable water supply is a critical characteristic for the microalgae biomass production. The adaptability of microalgae on the use of water is that they have the capacity to grow in both fresh and salt water, but also in wastewater (Godos et al., 2010; Kim et al., 2010; Kong et al., 2010), which reduces the costs in nutrient supply, low-quality water, such as agricultural runoff or municipal, industrial or agricultural waste- waters, as a source of water for the growth medium as well as a source of nitrogen (N), phosphorus (P) and minor nutrients that can be utilized for the production of microalgae biomass (Becker, 1994; Dragone et al., 2010; Kleivdal et al., 2012).

2.6.4. Land

According to Renaud (2011), “algae growth systems can be built anywhere meaning they can be built on marginal land or in industrialized areas” (p.4). Physical characteristics, such as topography and soil, might also limit the land available for open pond algae farming. Topography would be a limiting factor for these systems because the installation of large shallow ponds requires relatively flat terrain (Darzins, Philip Pienkos, 2010).

2.6.5. CO_2

CO_2 represents a strategic input to the production systems of microalgae. Controlling CO_2 costs and losses represent a strategic advantage for the success of the facility. The system provides a double benefit in that CO_2 is necessary for algae production and it recycles fossil CO_2 instead of polluting the atmosphere with it (Pienkos & Darzins, 2009). According to Kumar et al., (2010), "unbalanced production of atmospheric CO_2 represents a major challenge to global sustainability. Technologies have thus been developed for enhanced biological carbon fixation (also referred to as CO_2 mitigation), and one of the most promising capitalizes on microalgae" (p.371).

The most important aspect of microalgae biomass production is the bio-fixation processes and with that capacity it promotes a more sustainable use of GHG, by coupling microalgae biomass production with existing power generation and wastewater treatment infrastructures (Doucha et al., 2005; Kadam 1997).

The concentration of the captured CO_2 will be most beneficial to the cultivation of microalgae as a direct use of exhaust gases from combustion will also contain other components, such as; nitrogen oxides (NOx) and sulfur oxides (SOx) that may have a negative effect both on growth effects and the final product. Norsker et al. (2010) showed that CO_2 may represent a substantial portion of the operating costs - by up to 10% depending on the scale and production system. The possibility of increasing the revenue from microalgae via carbon credits is probably the main attraction for investors (Schulz, 2006)

2.7. Economic assessment

While many consider the biological types of algae attractive for pursuing biofuel production, cost economics remains a significant issue. A minority of studies have been carried out in an effort to estimate the prospective price of algae biomass and biofuel as a means to evaluate if microalgae will eventually reach cost parity with fossil fuels.

This section focuses on the review of the economic assessments of algae biomass production with a specific discussion of the input assumptions used to derive microalgae product costs. It reviews the key features of the studies: choice of methodology, key input variables, and the way to cooperate between the products and co-products. The studies in terms of evaluation of the technology used are essentially focused on the two main categories, raceway ponds and PBR. In recent years, it has been possible to find some studies that focused on hybrid systems, with a combination of both technologies.

Benemann & Oswald, (1994) wrote what several consider to be the fundamental piece in the economics of microalgae production for biofuels. In 1994, they wrote a report to the United States Department of Energy (DOE), where they reviewed cultivation and harvesting processes and sketched a theoretical technique for achieving a highly efficient production process. Throughout their theoretical work they concentrated on the costs of CO_2 mitigation with microalgae production of biomass and future research and development needs are outlined. In their report on the economics of microalgae production they review, discuss, compare, and update the costs for major open pond system designs of previous studies already found in the scientific literature.

Tapie & Bernard (1988) performed a rigorous analysis of the available algae it found in the literature and during that process it was possible to identify and describe all data and costs applied for large-scale algae biomass production facilities. In the course of the study they modified and recomputed the costs to compare different production schemes. Tapie and Bernard reported total production costs of non-processed biomass ranging from $0.15 to $4.00/kg, from all available literature (1985 Dollars$). When Tapie and Bernard finally performed their review, it was possible to establish an analysis breakdown for a tubular PBR production system. One important element to take into consideration is that for this particular study, the PBR system was applied to a 10 hectare facility, which isn't representative of what other authors consider a common commercial sized facility and disregards the effect that risk and debt repayment can have on the true costs.

Grima et al., (2003) reported the production of P. tricornutum in tubular PBRs had a cost of $32 per kg dry biomass. These numbers can be compared to those reported by Chisti (2007) which assesses the technical feasibility of microalgae biodiesel production. During the study, Chisti argued and pointed out that biodiesel from microalgae performs better than petroleum diesel, but its relatively high production costs and the limited availability of some microalgae biodiesel production methods must be drastically changed to be competitive when compared with fossil fuels. It is still expected to be a real game-changing breakthrough regarding algae costs. For PBR and open pond facilities producing 100,000 kg of biomass annually it is estimated that the cost per gallon of production is $2.95 and $3.80, for PBR and open ponds, respectively (2006$).

Shen et al., (2009) demonstrated during this article review the overall performance, special features, and technical and/or economic barriers of various microalgae biomass production techniques including open-pond, PBR, and immobilized culture systems. During the study it was possible to identify the PBR system as the cheapest method used for producing microalgae biomass. However, issues of vulnerable strains contamination, low productivity, high harvesting cost, and a large volume of water loss have to be addressed. High biomass productivity and cell density, reduced contamination, and better use of CO_2 are some of the significant advantages of PBR, but the excessively high capital costs during the construction and implementation phases of the project, represent a major drawback for this particular technology method.

Norsker et al., (2010) establishe a base line comparison between three different system technologies for the cost of producing microalgae, under Dutch climatic conditions. The three different technologies applied in the study were; open ponds, horizontal tubular PBR and flat panel PBR. In the study for the 3 systems, resulting biomass production costs including dewatering, were 4.95, 4.15 and 5.96 euros (€) per kg, respectively. The significant cost factors are irradiation conditions, mixing, and photosynthetic efficiency of systems, medium- and CO_2 costs. Optimizing production with respect to these factors, a price of € 0.68 per kg resulted. At this cost level, microalgae become a favorable feedstock for biodiesel production and bulk chemicals.

Davis et al., (2011) published a recent and innovative study with the goal of establishing a baseline techno-economics comparison for two microalgae pathways systems. The study was accomplished with a broad analysis using a number of assumptions of what can reasonably be achieved within a five-year timeframe. Precise pathways systems include autotrophic production via both open pond and closed tubular PBR systems. The production scales were set at 10 million gallons per year of raw algal oil, subsequently upgraded to a "green diesel" blend stock via a process called hydro treating. They found minimum selling prices for lipid of $ 8.52/gal for open ponds and $ 18.10/gal for PBR (2007 dollars ($).

Lundquist et al., (2010) assessed the economics of microalgae biomass production through a detailed analysis of five different production scenarios. The scenarios were developed according to the technology available at the moment, and that is expected to be developed in the near future. The study executed a techno-economic assessment with a process flow diagram methodology. This paper focused on the potential of algae bio-fuel production in conjunction with wastewater treatment and fully integrates the wastewater treatment in the process design and economics. The cost of the product is presented in Table 3. It is necessary to notice the importance of co-product and co-service in this specific study.

Table 3 Summary of cost of algae production (Lundquist et al., 2010)

Study			Cost of Product (without co-product/co-service)	Cost of Product (with co-product/co-service)	
Lundquist, et al., 2010	Algal Oil	Case 1	315€/bbl	Wastewater treatment	21€/bbl
	Electricity	Case 2	0.47€/kWh	Wastewater treatment	0.13€/kWh
	Algal Oil	Case 3	305€/bbl	NA	250€/bbl
	Electricity	Case 4	0.67€/kWh	NA	0.54€/kWh
	Algal Oil	Case 5	228€/bbl	Wastewater treatment	180€/bbl

Darzins et al., (2010) report covers the potential benefits of microalgae biomass production, algal cultivation, algal harvesting, extraction of algal oils, fuel production from algal feedstocks, and related topics. This study is part of the International Energy Agency (IEA) Task 39 projects. One of the activities of *IEA* Bio-energy Task 39 is to commission state-of-the-art reports on some of the most important significant clean energy developments. This report seeks to examine the techno-economic feasibility of generating microalgae biomass for the production of bio-fuels. The cost of the product is presented in Table 4.

Table 4 Cost of algae production (Darzins et al., 2010)

Study			Cost of Product (without co-product/co-service)	Cost of Product (with co-product/co-service)	
Darzins, et al., 2010	Algae Oil (NREL)	Roswell case	4.37 €/L	Animal feed/Biomass for ethanol	4.0 €/L
		High oil content	1.9 €/L	Animal feed/Biomass for ethanol	1.63 €/L
		High productivity	0.56 €/L	Animal feed/Biomass for ethanol	0.52 €/L
	Algae Biodiesel Australia	Best scenario	0.48 €/L	Animal feed	225 €/ton

Zamalloa et al., (2011) reported that the potential of microalgae as feedstock for CH_4 production is evaluated from a technical process and economic point of view. The production of mixed culture algae in raceway ponds on non-agricultural sites, such as landfills, was recognized as a preferred approach. Fundamentally, algae biomass is used to produce energy (electrical and thermal) through anaerobic digestion. An important assumption in the study is that the authors consider the value of CO_2 as free in the process.

Bogle & Fairweather (2012) established a systematic method for the economic and environmental analysis and design of new technologies applied to the 3rd generation (from microalgae) biodiesel production process. The evaluation method is based on the integrated use of process simulation techniques with economic and environmental models. The approach is applied to a new technology introduced by some of the authors, where the glycerol produced in the trans-esterification is used as the carbon source for microalgae growth. This study focused on the use of LCA as the primary tool for developing the results.

Richardson et al., (2010) demonstrated using a Monte Carlo financial feasibility model an estimation of the costs of production and chance of economic success for a commercial size algae bio-fuel facility. Capital and operating costs and productivity statistics were extracted from Davis et al., (2011) and used to try to develop parameters to define and simulate two types of algae production systems; open pond and PBR. The total costs of algal oil ranged from \$0.85 to \$3.67 pound, with an average of \$1.61 (with by-product credits) for the conventional wisdom input/output coefficients.

Ribeiro & Silva (2013) performed an ample review of the scientific literature, contributing to the analysis of cost, economic and technical indicators. The outcome of the results obtained provided key information gaps of important and crucial information that need to be filled, so as to in order to establish a regulation of possible future investment decisions towards a rising of the technology. An important conclusion from the authors is that after performing a costs assessment of different algae cultivation techniques, is possible to identify an economic stance towards large-scale production of algae biodiesel, presently the production of algae biodiesel is still not a viable alternative when compared to petroleum-based fuels.

2.7.1. Conclusion of the economic assessment

The central conclusions that are possible to extract from this review of all the articles are:

- A wide range of production costs are reflected according to the assumptions defined for yields, capacities, costs and the state of technology developed.
- The lack of conciseness of the numbers available and the dependence on parameters extrapolated from lab-scales analyses. For instance, some of the data and assumptions used in the studies are old and as a consequence may not reflect the actual state of microalgae production.
- The great potential for reducing GHG emissions on a global perspective is one of the strategic matters in microalgae, from an environmental point of view.
- The development and economic viability of microalgae is still dependent on subsidies. Subsidies might allow the possibility of microalgae biodiesel to be produced economically under some specific conditions.
- The production of co-products, or provision of co-services, significantly affects the economic and environmental viability of the projects. Adding value to these co-products and co-services is of great economic

significance. If the co-products are properly used, their energy can contribute significantly to the reduction of production costs and possibly for self-reliance in energy production units.

3. ALGAE PRODUCTION COST

This chapter focuses on the real problem presented for this dissertation. It first introduces the basic concepts for the economic assessment and describes the methodology that was selected for conducting this study. Chapter 3.1 illustrates how the economic methodology described in chapter 1.4 can be applied for the specific case-study.

3.1. Cost analysis

The cost analysis attempts to find a breakdown between the various design parameters or process operations, manufacturing and investment cost. The preliminary economic evaluation of a project for manufacturing of microalgae biomass usually involves the estimation of the capital investment and operation costs. Table 6 presents and identifies the reasoning for the main elements of the total product cost as they are defined.

Table 5 Production cost of microalgae biomass (adapted from Kalk & Langlykke, 1986)

- ***I.* Direct operation cost**
  - A. Raw materials and supplies
    - 1. Raw materials
      - a) Primary
      - b) Secondary
    - 2. Supplies
      - a)Operating
      - b) Maintenance
      - c) Laboratory
      - d) Other
    - 3. By-Products
  - B. Labor and Supervision
    - 1) Base salaries and wages from detailed manpower estimate
    - 2) Fringe benefits
  - C. Utilities
    - 1. Steam of Fuel
    - 2. Electricity
    - 3. Water
- ***II.* Fixed costs**
  - A. Depreciation and interest of fixed capital for depreciation
  - B. Taxes
  - C. Insurance
  - D. Rent (High variable)
- ***III.* Plant overhead**

For cost estimation:
Production cost = *I*+*II*+*III*

To review the present production cost of the microalgae biomass produced in the defined technology facility it is required to describe the flowchart of the process in detail. The first and most important step is to define the list of equipment and its size (Kalk & Langlykke, 1986).

Production costs are divided into: *i*) direct operating costs for the microalgae production facility mainly consist of direct labor, maintenance expenses, utility costs and raw materials expenses. The total operating expenses are estimated and assumed to remain constant throughout the model assumed period. *ii*) Fixed costs which are charges for capital investment in the production facility. *iii*) Plant overhead costs, that are usually defined as items not detailed in the production estimation scenario and usually are those applied to indirect labor and cost (i.e. rent, light, heat, security, etc.)

The total production cost can be calculated as the sum of the depreciation plus the direct production costs. The depreciation includes not only amortization of the fixed capital, which is a function of the lifetime considered for the project (15 years), but also the property tax, insurance and purchase tax.

The direct production costs were estimated according to the literature review or engineering estimates. Direct production costs include raw materials, utilities and labor. The total amount of raw materials used can be calculated from mass balances according to the explicit flowchart of the technology used, while the consumption of the utilities can be calculated according to the power and water used in the process. To calculate the direct production cost is it essential to know the cost of the raw materials, utilities and staff, although the other costs can be found according to the factors previously set.

The different types of investment costs for a production plant need to be distinct. They include the major equipment, subcomponents such as piping and construction as well as installation costs. Major equipment – i.e. machinery and apparatus – are defined first in the valuation process and usually represent 25 to 40 percent of the investment costs (Remmers, 1991).

The actual cost of the major equipment has to be defined giving the values established in the literature, and according to some engineering calculations. The total fixed capital can be calculated after the major equipment breakdown (Table 6) cost is known, by multiplying the corresponding Lang factors based on the nature of the item, which gives the true estimated cost for the equipment and activities. These costs can include installation cost, engineering and supervision, instrumentation and control. In the Lang method (Lang, 1948) the FCI of the manufacturing facility can be estimated with Lang's factor from the cost of the purchased equipment of the plant (R.G. & P.W., 2003)

Table 6 Fixed costs assumptions (adapted from Hacking, 1986)

Item	Detail	Factor
1	Major purchased equipment	1.00
2	Intallation costs	0,20
3	Intrumentation and control	0,15
4	Piping	0,20
5	Electrical	0,10
6	Buildings	0,23
7	Yard improvements	0,12
8	Service facilities	0,20
9	Land	0,06
10	Engineering and supervision	0,30
11	Construction expenses	0,05
12	Contractor´s fee	0,03
13	Contigency	0,08
	Total fix capital	
Item		
1	Lifetime	15
2	Depreciation	
3	Property tax (at 0.01 depreciation)	0,01
4	Purchase tax (at 0,16 of items 1-12/10)	0,16
5	Insurance (at 0.006 depreciation)	0,01
Total fix capital per annun		

Source: adapted from Kalk and Langlykke, 1986

The cost estimation is presented in Table 6. It depends on the values applied on the multiplication factors. Although it is presented in the table as a fixed value, the multiplication factors frequently are within a precise value range. The value chosen it is generally weighted according to a different set of categories, such as; location, type and size of the plant. Fixed capital is usually divided into different categories; this includes direct costs and indirect costs (Table 7). Each of these components can be estimated separately. Its magnitude will vary considerably according to the nature of the project.

Table 7 Fixed capital divided in direct and indirect costs

A. Direct Costs	B. Indirect Costs
1. Intallation costs	9. Engineering and supervision
2. Intrumentation and control	10. Construction expenses
3. Piping	11. Contractor´s fee
4. Electrical	12. Contigency
5. Buildings	
6. Yard improvements	
7. Service facilities	
8. Land	

A. Direct costs

The most important cost item in the estimation process is the acquire and the installed equipment cost, mainly because it is a major part of the fixed-capital investment and also because it is used as a base for the estimation of the remaining cost objects (Heinzle, Biwer, & Cooney, 2007). Instrumentation and control includes all auxiliary equipment and instruments for controlling and recording the different variables at each stage of the process. Piping represents all pipes, hangers, valves and pipe insulation and their installation. Electrical systems characterize all electrical equipment (switches, motors, wires etc.) and electrical materials used in the facility. Buildings process and auxiliary are all offices, warehouses, laboratories and building services (plumbing and HVAC etc. systems). The land and yard improvement costs consist of all necessary capital for land surveys and fees, the property cost, and yard improvements such as expenses for site development (site clearing, grading) and landscaping, roads, walkways, railroads, fences, parking areas, etc. The established definition for services facilities for a process is the structures, equipment and services not directly involved in the process. Usually, these comprise equipment for the supply of steam, water, electricity, compressed air and fuel (Bejan & Moran, 1996; Ereev & Patel, 2012;)

B. Indirect Costs

This includes costs that are not directly involved including engineering and supervision. It includes expenses for administration, process design and general engineering, computer graphics, cost engineering, communications; as well as consultant fees, travel expenses and engineering supervision and inspection. The category for construction expenses and contractor’s fee includes all costs for construction, operation, maintenance of temporary facilities, offices, roads, communications and fencing; all expenses for construction tools and equipment, supervision, accounting, timekeeping and purchasing. Extra costs such as warehouse personnel and expenses, guards, safety, permits, taxes, insurance and interest are projected as part of this cost object (Bejan & Moran, 1996; Ereev & Patel, 2012; Drapcho, Nhuan, & Walker, 2008). Contingency is the uncertainty as to the precise content of all items in the estimate, which is sometimes also referred as backup capital (Jelen, Black, & Engineers, 1983).

3.2. Production process

3.2.1. System boundaries

The process begins with the algae growth, which is provided by the addition of CO_2, nutrients and water.

In this process, the following general assumptions are made:

- All input factors of the process (microalgae, water, nutrients, labor, maintenance, power consumption, land) are bought and not generated within the system itself.
- All equipment and utility costs are indicated and calculated.
- The use of high-value co-products to support the profitability is not taken into consideration.
- Total operating expenses are expected to remain constant throughout the model.

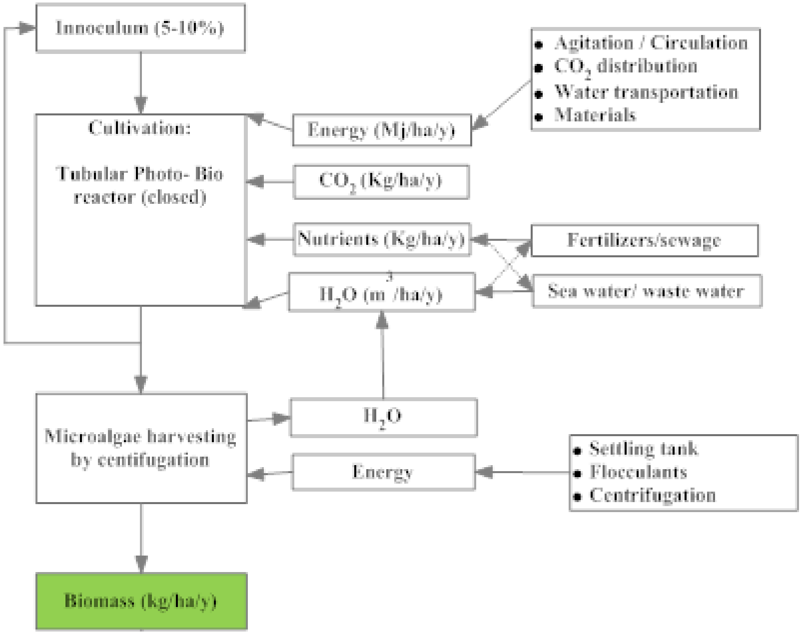


Figure 5 Simplified flowchart of a hybrid algae biomass production system used for the economic analysis. Note that various other options exist for conversion of biomass and residues.

The first step in algae culture is the preparation of the growth media. Culture medium is prepared and sterilized and later added to the PBR in the daylight period. The process includes automatic preparation of the culture medium by adding fertilizers to water. Fertilizers are pumped daily to the PBR and the harvested material is continuously centrifuged. The culture medium is circulated through the PBR using a centrifugal pump.

The harvesting of the biomass requires one or more solid–liquid separation steps. In the case-study, the chosen method for harvesting biomass was centrifugation. These processes may be preceded by a flocculation step that was not considered in the process. The strategies provided by Chisti & Moo-Young (1991) for selection and use of centrifuges are especially significant to the recovery of the microalgae biomass. Centrifugal recovery can be quick, but it is very energy intensive (Benemann et al., 1980; Mohn, 1980; Richmond, 1986).

3.2.2. Description of the scenario

The focus of entire study project is set in southern Portugal. This assumption implies that the site location is a key essential factor for the project. The solar irradiation in Portugal ranges from 14 to 17 *MJ/m^2.day* (Figure 6).

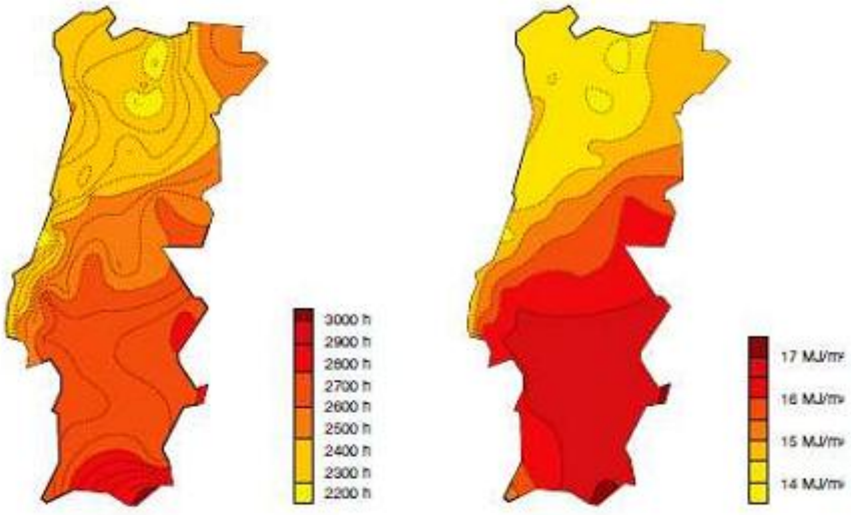


Figure 6 Global horizontal irradiation, Portugal (Rui Aguiar, 1998)

The literature shows that the solar radiation in southern Portugal (Algarve) is extremely favorable, with an average 17 Mj/m2.day. The Algarve boasts a fantastic Mediterranean climate with an annual average of 3000 sunshine hours. The summer months average 12 hours of sunshine per day with almost no rain. It is possible to conclude that algae production in this area will benefit from high insulation (Aguiar, 2006).

The temperature from June till September starts out in the mid 20ºC and reaches a peak of 28ºC in July and August. In September the temperature drops down to 26ºC. From December till February, is very mild with an average high temperature of 16ºC in December and February which drops just slightly to 15ºC in January (Oliveira, 2002). Furthermore, the cost items for example labor costs are country-specific.

3.2.3. Parameters for the production system

The production system should be built on 0.1 ha and requires an additional 30 percent for supporting production facilities (Norsker et al., 2011). General parameters defining the production system are chosen in accordance with the economic model. The production system should be built on a 0.1 ha production facility.

Table 8 General conditions and parameters for the production system

General conditions and parameters	Value	Unit
Net production area	0.1	há
Land area	0.13	há
Lifetime of PBR	15	years
Operation days	330	days

The facility is assumed to operate 11 months for year (330 days). January is a key month for the production based on the temperature, and the month will be used for PBR maintenance and cleaning of the facilities. The calculations were carried out at a plant scale of 0.1 ha. The microalga used was *Scenedesmus almeriensis* mainly due to important applications in aquaculture of carotenoids for animal/human food additives market. Scenedesmus almeriensis is a fast-growing highly productive new strain with requirements for freshwater, their biomass is a source of carotenoids, particularly lutein, the potential market of lutein is around 90 million people in the world and increasing. (Macías-Sánchez et al., 2010).

The PBR engineering features are assumed to be 100 tubular photo-bioreactors with a respective volume of 0.8 m^3 in each one, with a total volume of 80 m^3 for the entire large-scale production system. PBR closed systems don´t face any evaporation problem (Davis et al., 2011a). The culture medium is pumped daily to the PBR and the harvest is continuous. The volume to surface ratio is 0.08 m^3/m^2 and the culture is circulated through the PBR using a centrifugal pump.

The yield of the facility is determined on an annual basis and operates on a continuous mode at 0.40 l/day. The optimal dilution rate for *Scenedesmus almeriensis* has been found to be between 0.3 and 0.4 l/day (Sánchez et al., 2008). Considering the V/S to the reactor is 0.08 m^3/m^2 the maximum values of biomass concentration 1.82 g/l can be obtained, it was assumed to have 1.65 g/l for the case (Acién et al., 2012). During the year, the productivity ranges with maximum month productivities and minimum month productivities that are always associated with the solar irradiation and temperature available. The estimate for the annual average productivity is conservative. As an example, in contrast, the techno-economic study of Benemann & Oswald (1996) projected much higher productivities. For the PBR system it was assumed a biomass productivity of 0.66 g/l/day (Acién et al., 2012) (Table 9) with a total annual production of 17.45 Tn/year. In the end of the process it is possible to obtain a 15% dry matter contain.

Table 9 Main parameters defining the process

Ratio V/S	0.08 m^3/m^2
Dilution rate	0.40 l/day
Biomass productivity	0.66 g/l day
Biomass concentration	1.65 g/l
Operation time	330 days
Total cultural volume	80 m^3
Total cultural surface	0.1 ha
Annual production	17.45 Tn/year

3.3. Capacitive adjustment

The costs for the major equipment stated in Chapter 3.3 are related to a capacity, which needs to be adjusted to the requirements of the microalgae biomass production facility of this case study. For up-or downscaling of the costs of the production equipment, linearity is not assumed as economies of scale can be realized (Gerrard, 2000). For the rest of the PBR material, an exponential scaling factor for the ratio of capacities of 0.85 is taken (Acién et al., 2012) and inserted for n in Equation 1. In detail, the PBR is adjusted by multiplying the intended total reactor volume of 80 m^3 with the costs per module for the volume in Table 10.

The culture medium preparation unit for a PBR volume of 60 m^3 (Grima & Belarbi, 2003) is scaled up by the respective PBR volume of 80 m^3. The CO_2 supply station is adjusted by the dispensing capacity, which is 4 kg/h (Acién et al., 2012), and in this study is 9.6 kg/h. Assuming that CO_2 needs to be provided within 10 hours,. production time set for this case. With a CO_2 condition of 1.83 kg DW algal biomass, a production rate of 0.66 g DW algal biomass/(l*d) and a PBR volume of 80 m³, the supply capacity are the above indicated 9.6 kg/h. The centrifuge and the associated feed pump are scaled up to be able to process the PBR volume of 80 m³ resulting in a necessary capacity of 3.98 m^3/h.

3.4. Economic Inventory

The economic inventory describes and justifies the chosen production processes and systems for microalgae biomass production on the PBR system.

3.4.1. Use phase for biomass production

The growth phase of *Scenedesmus almeriensis* needs – apart from the algae culture – the input of water, CO_2 and nutrients as well as solar irradiation. The necessary CO_2 supply is bubbled into the PBR to feed the algae. The bulk of CO_2 introduced to the system is usually a management control tool variable and is closely connected to the production of algae biomass. The necessary CO_2 supply diverges depending on the algal species between 1.65 (Morweiser et al. 2010) to 1.85 (Posten 2009) times the algal dry weight. The CO_2 cost in the literature ranges between €0.0026-0.40 of biomass produced (Andersson et al., 2011). According to Chisti, 1 kg of dry algal biomass utilizes about 1.83 kg of CO_2 (Chisti, 2007), so for the given designs CO_2 is considered as 1.83 kg of CO_2. The cost of CO_2 chosen was 0.30 €/kg (Acíen et al., 2012).

The medium cost variable is the cost per cubic meter of the algae nutrients. The growth medium must provide the inorganic elements that constitute the algal cell (D’Elia et al., 2010). Nutrient cost information was very difficult to obtain since the nutrient mixes are guarded very seriously by people inside the industry. This model bases the annual nutrient costs used according to Grima and Belarbi, 2003 which states that it usually takes 2.5 kg of medium to produce 1 kg of algae biomass in a PBR. Nutrient losses that occur during the entire production process are not take in consideration. The literature suggest a value of 0.55 €/kg of medium (Molina Grima et., 2003). All the assumptions regarding the case-study for the use phase are presented next in Table 10.

Table 10 Direct operation costs assumptions

Raw materials	**€/unit**	**Source**	**Notes**
Fertilizers (kg)	0,55 €	Molina Grima et al., 2003	Takes 2.5 kg of medium to produce 1 kg of algal biomass in photobioreactor
Carbon Dioxide (kg)	0,30 €	Acíen et al., 2012	Takes 1.83 kg of CO_2 to produce 1 kg of biomass
Utilities			
Water (€/m3)	0,10 €	Calculated in water requirements	Section 3.6
Power consumption (kWh)	0,10 €	Calculated in Energy requirements	Section 3.5
Other operation costs	**unit**	**Source**	**Notes**
Labor	6,00	Wages and labour costs - Statistics Explained (2013/6/4)<http://epp.eurostat.ec.europa.eu/statistics_explained/index.php/Wages_and_labour_costs>	Assuming cost of hour 12.10€ and 40 hours week
Supervision (at 0.2 labor)	0,20	(Acíen et al., 2012; Ereev & Patel, 2012; Frioui & Oumeddour, 2010; Silla, 2003)	
Payroll charges (at 0.25 labor+supervision)	0,25		
Maintenance (at 0.04 Major Equipment Cost)	0,04		
General plant overhead (at 0.55 (labor+supervision+maintenance)	0,55		
Contingency (at 0.05 items 1-7)	0,05		
Marketing (at 0.05 items 1-11)	0,05		

3.4.2. Capital investment – phase

Capital cost increases for the construction phase; they contain the installed production equipment and other auxiliary facilities. These cost items are the most important ones identified by several other comparable studies where the relevant cost items for the production process are similar (Acién et al. 2012; Molina Grima et al. 2003). The PBR construction costs of the capital investment phase are projected by using the resulting costs as presented in Table 11. The model gives each of the particular assets a useful life and depreciates the equipment based on the useful life of the asset. The majority of the equipment is assumed to have a useful life of 15 years. Annual depreciation is expected to decrease as the useful life expires on the assets. Generally the cost is allocated, as a depreciation expense, among the periods in which the asset is expected to be used.

Temporal adjustment is done by harmonizing all cost items to 2013 prices. Due to the focus on Portugal, inflation adjustment for the specific services and products were established according to inflation.

Table 11 Production equipment for the PBR systems (Major purchased equipment)

Production equipment	Price per unit	Year	Capacity	Source
Photobioreactors	3.376,00 €	2003	0.8 m^3	Molina Grima et al., 2003
Culture medium preparation unit	33.265,00 €	2012	19,96 m^3	Molina Grima et al., 2003
Carbon dioxide supply station	1.000,00 €	2003	4 kg/h	Acíen et al., 2012
Centrifuge	183.000,00 €	2003	2,99 m^3/h	Molina Grima et al., 2003
Harvest feed pump	1.000,00 €	2011	12.5 m^3/h	Acíen et al., 2012
Harvest broth storage tank	34.814,00 €	2011	60 m^3	Molina Grima et al., 2003
Culture medium feed pump	6.000,00 €	2003	12,5 m^3/h	Norsker et al., 2007
Biomass Silos	1.300,00 €	2003	0,07 m^3	Molina Grima et al., 2003
Sterilization process	15.000,00 €	2012	2 m^3/h	Acíen et al., 2012

After the process of scaling up of the major equipment, it was possible to determine the real cost of the production facility, given in the results section.

3.5. Energy requirements

Energy consumption is associated with all aspects of the project that include some kind of energy input. For the PBR, the pumping energy per square meter depends on numerous factors such as pressure drop, density, viscosity and Reynolds number and tube diameter (Burgess et al., 2007). In this specific study, the designated energy requirements are mainly taken from the same studies that are also the basis for costs and capacitive adjustments. For biomass production and harvesting, the power requirement is given per PBR volume and presented in Table 10. The CO_2 required is related to the amount of CO_2 pumped in the process. The biomass itself can be used for biogas production to generate electricity; however methane production by anaerobic digestion for generation of electricity was not taking in consideration for the case-study.

Table 12 Energy requirements of the process

Production equipment	Value	Unit	Total Kwh	Source
Biomass production				
Culture medium preparation unit	0,28	kWh/m^3	5420,8	Acíen et al., 2012
Culture medium feed pump	0,13	kWh/m^3	2516,8	Norsker et al., 2011
CO_2 injection	22,2	kWh/tCO_2	708,85	Kadam, 2001
Pumping for cooling	0,13	kWh/m^3	2517,97	Norsker et al., 2011
Harvesting				
Centrifuge and feed pump	4	kWh/m^3	77440	Patel et al., 2006

3.6. Water requirements

In terms of water requirements for the production system, usually water supply-costs are dismissed, since the microalgae biomass is grown in saltwater, which is free of charge (Acién et al., 2012; Molina Grima et al., 2003; Norsker et al., 2011). However, in this particular study, water will be taken into consideration, mainly because the microalgae strain grows with the requirement for fresh water.

All water requirements can be divided in two sources: Fresh water and sea water. In the case study, fresh water was used as the source of photosynthesis for the culture, and seawater was used for free for the requirements needed for the cooling of the production process, since PBR heats significantly under high radiance conditions. For avoiding the use of freshwater for the cooling system, sea water will be used as an alternative, since the quality of the water is not a key issue for the cooling system. Evaporation won’t be taken into account, since it will be assumed that in the case of a closed cultivation system there will be no evaporation (Lundquist, et al., 2010).

The necessary annual quantity of freshwater for the culture medium can be determined by the PBR volume, which is 80 m^3. The culture medium is changed after three batches, in case the system doesn´t replace the culture medium, both expensive filtration and sterilization steps for culture medium water recycling would be further needed because of culture contamination by bacteria (Alabi et al., 2009). Give the total volume of the PBR, 80 m^3, and the number batches needed to be replaced; the total amount of freshwater needed for the total amount of batches is 8800 m^3/year. Considering the dilution rate of

0.4 l/day, and a total volume of 80 m^3 assuming 330 days of operation, it is possible to estimate a volume of 10560 m^3. This requires a total amount of water of 19360 m^3/year.

4. RESULTS

4.1. Break down of the production cost

The key cost and process assumptions used in calculating the results presented in this section are summarized in the Appendix A. The list of equipment necessary is presented in Table 13, along with its individual cost. The total major equipment cost for the PBR is about 700.209, 00 €

Table 13 List and cost of the major equipment for the case study

Production equipment	Cost in Euro
Photobioreactors	337.600,00 €
Culture medium preparation unit	42.703,75 €
Carbon dioxide supply station	2.100,00 €
Centrifuge	232.410,00 €
Harvest feed pump	2.300,00 €
Harvest broth storage tank	44.213,78 €
Culture medium feed pump	1.080,00 €
Biomass silos	3.302,00 €
Sterilization process	34.500,00 €
Total	700.209,53 €

The photobioreactors and the centrifuge represent the largest amount invested for the capital cost, totaling 48 %, and 33 % respectively (Figure 7). Photo-bioreactors represent the highest cost item in all microalgae cultivation. The high capital costs of PBR are due to the costs of construction materials, circulation pumps, nutrient-feeding systems and costs for implementing the software of the technology. Centrifuges are usually the option chosen for the algae industry and they are capital and energy intensive.

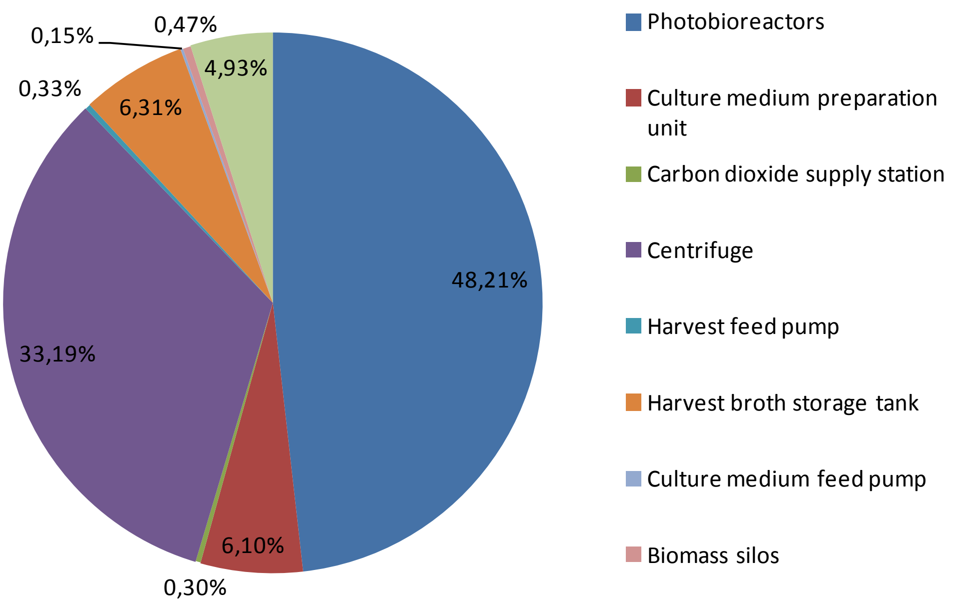


Figure 7 Pie chart of the major production equipment for the case study

Fixed capital estimated was calculated based on the major production equipment. Fixed capital is the amount of money required to completely construct the microalgae production plant with auxiliary services, and to carry it to the point of start-up production. It is essentially the total value of all the assets of the microalgae production plant. In the case study, the major equipment, installation costs, piping, buildings, engineering and supervision and finally contingency are the most important components increasing the cost as summarized in Table 14. Major equipment cost and engineering and supervisionrepresent the largest share components of the fixed capital necessary for the startup of the facility, contributing with 35 % and 11 % respectively (Figure 8).

The total fixed capital required to get the facility setup and ready for production is around 1.997.697, 00 €. With a lifetime of 15 years, the annual fixed capital in the production facility is around 154.329, 00 €.

Table 14 Total fixed capital estimated for the case study

Item	Detail	Factor	Cost
1	Major equipment	1,00	700.209,53 €
2	Intallation costs	0,20	140.041,91 €
3	Instrumentation and control	0,15	105.031,43 €
4	Piping	0,18	126.037,72 €
5	Electrical	0,10	70.020,95 €
6	Buildings	0,23	161.048,19 €
7	Yard improvements	0,10	70.020,95 €
8	Service facilities	0,20	140.041,91 €
9	Land	0,06	42.012,57 €
10	Engineering and supervision	0,30	210.062,86 €
11	Construction expenses	0,05	77.723,26 €
12	Contractor´s fee	0,03	46.633,95 €
13	Contigency	0,07	108.812,56 €
Total fixed capital			1.997.697,79 €
Item			
1	Lifetime	15,00	
2	Depreciation		133.179,85 €
3	Property tax (at 0.01 depreciation)	0,01	1.331,80 €
4	Purchase tax (at 0,16 of items 1-12/10)		19.018,81 €
5	Insurance (at 0.006 depreciation)	0,01	799,08 €
Total fixed capital per annun			154.329,54 €

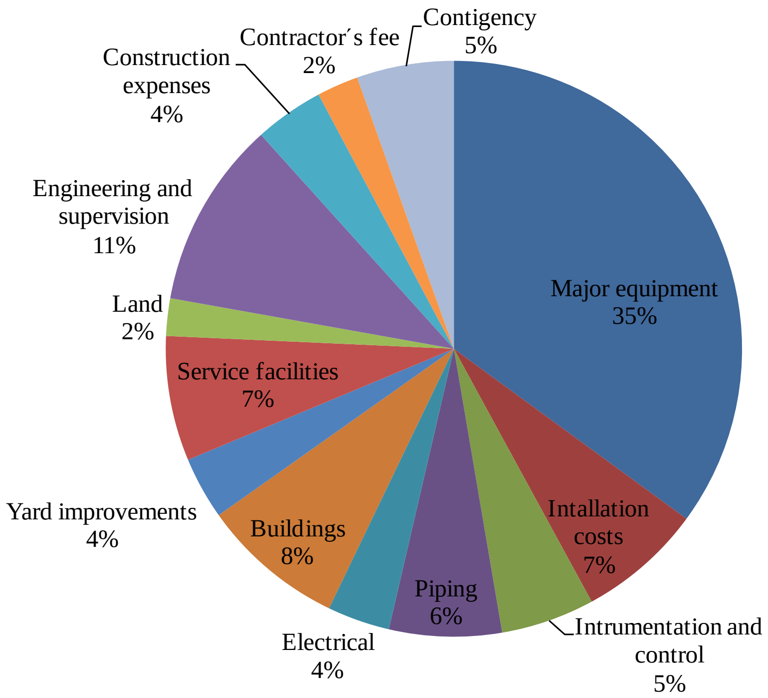


Figure 8 Capital cost components breakdown by categories for the case study

The direct production costs that arise from the case study were also calculated. The raw materials, utilities and labor are the main entries selected in this specific case. Table 15 displays the various types of direct production costs used in the operation process. Some cost items are categorized as either fixed or variable. The total value for the direct production cost is 33.523,00 € for the raw materials, 10.796,44 € for the utilities and 238.511,00 € for labor. Utility expenses include the costs associated with operation of the harvesting, mixing subsystem and pumping requirements.

In the raw materials, the fertilizers used in the process are the most relevant cost for the system, accounting a value of 23.958,00 € for year. Inside the utilities categories, power consumption represents the largest cost category, with a value of 8.860,00 € per year. In the labor category, the value defined for the direct labor represents the most relevant category, with an approximate value of 163.800,00 € (Table 15)

Table 15 Direct production costs for the case study

Item	Raw materials	Total cost
1	Fertilizers (kg)	23.958,00 €
2	Carbon Dioxide (kg)	9.565,78 €
Item	**Utilities**	
4	Water (€/m3)	1.936,00 €
5	Power consumption (kWh)	8.860,32 €
Item	**Labor and others**	
6	Labor	163.800,00 €
7	Supervision (at 0.2 labor)	6.552,00 €
8	Payroll charges (at 0.25 labor+supervision)	10.647,00 €
9	Maintenance (at 0.04 MEC)	1.518,17 €
10	General plant overheads (at 0.55 (labor+supervision+maintenance)	54.752,20 €
Total raw materials		33.523,78 €
Total utilities		10.796,32 €
Total labor and others		237.269,37 €

For the case study and assumptions applied, is possible to estimate a microalgae biomass cost of 23.82 €/kg. The production cost of algae biomass is broken down into cost categories and shown in Figure 7. For the case-study, the labor with 57.00 % is the major cost component followed by the depreciation with 32 %, raw materials with 8.00 % and utilities with 2.60%. Labor and depreciation are the most relevant categories of the final production cost, though the costs related to the raw materials and utilities were much lower.

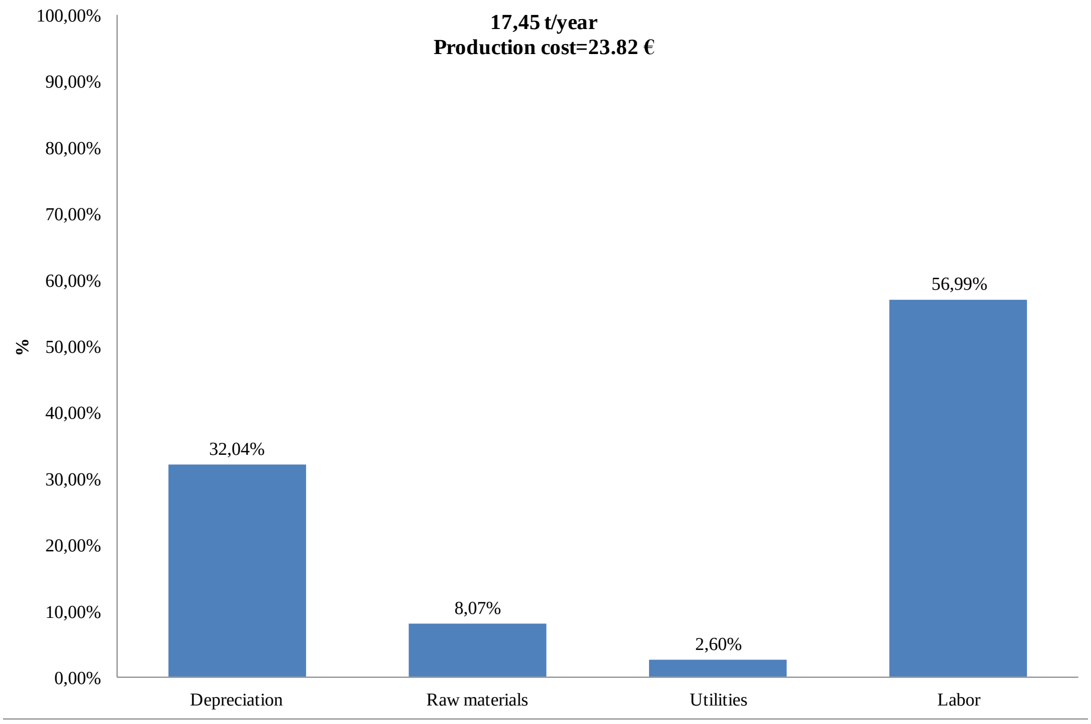


Figure 9 Major productions cost for the case study

Labor is the major cost component of the final cost of the production. The value of the labor is estimated based on the statistical values used for Portugal. It is not surprising that labor costs - a major operational cost component - are ranked as the most important site selection factor by corporate executives when facing a decision regarding the investment in a new facility. Depreciation is a present expense that accounts for the past cost of an asset that is now providing benefits. In our case study, it also represents a large share of the final price of the product (32.04%). The value could be even higher if the lifetime value of the asset would be considered lower, in this particular case, 15 years was the lifetime that was expected.

The labor costs are very scale dependent, always depending on the exact location of the investment. Inside the labor category (Figure 10) it is possible to identify the most relevant categories, where direct labor of 68.68 % and general plant overhead with 22.96 %, represent the categories that have the most influence on the final price. The direct labor cost is a part of the payroll that can be precisely and constantly assigned within the manufacture of a product. In this particular group, the values are assumed to be around 163.800,00 € (table 15).

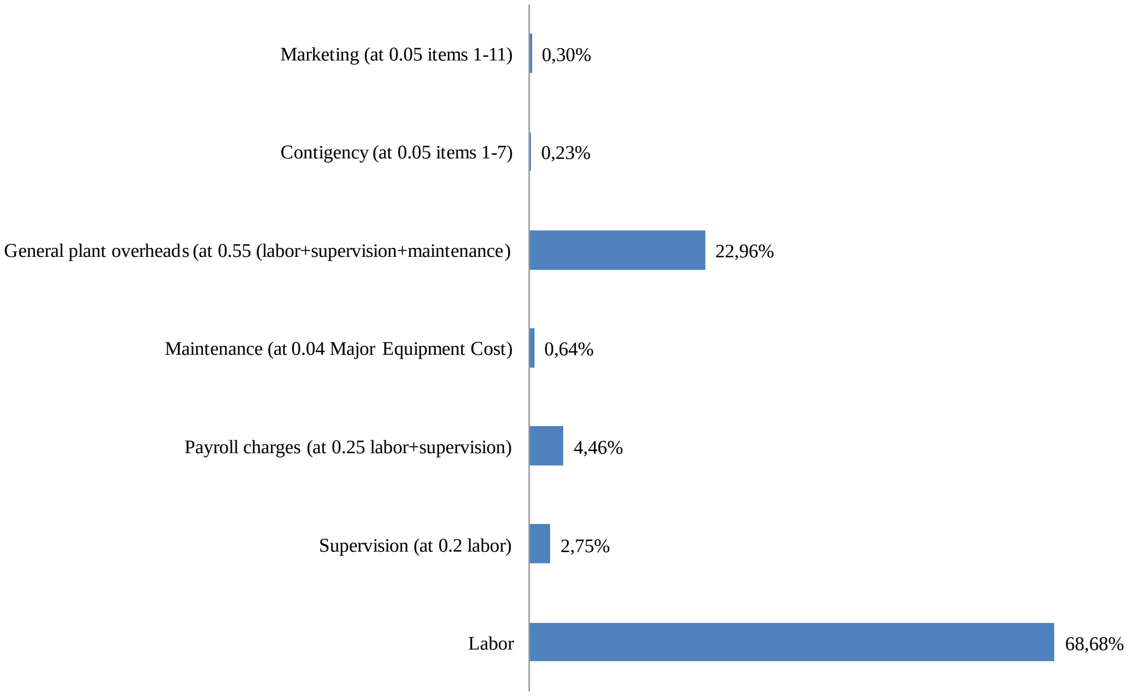


Figure 10 Labor cost category for the case study

General plant overhead costs provide a general category for acquired costs that do not fit into the previous cost categories. Overhead costs represents 54.752, 20 € of the total amount related to production and assembly activities but which cannot accurately be charged on a direct source to a particular product. Together with depreciation and direct labor they represent a tremendous cost driver of the overall microalgae production system cost.

4.2. Scenario analysis

Scenario analysis permits a response to a set of questions "What If" identifying changes in solution of the optimal problem when there are variations in the model parameters. It seeks to identify biological and engineering parameters which are most important in reducing microalgae unit cost. A scenario comparison was run for several alternative scenarios to evaluate the future of microalgae production cost. In addition to the base line case study developed in the dissertation, a maximum growth scenario and a strong scenario with a comparison to the base case will be developed. The PBR assumptions were assumed to be 0.66 g/l/day for the base case, 1.5 g/l/day for a high productivity case and 3g/l/day for maximum growth (R. Davis, Aden, & Pienkos, 2011b).

The ‘‘high productivity’’ scenario is proposed to represent possible longer-term research advancements in strain perfection, while the ‘‘maximum growth’’ scenario is established near the theoretical maximum growth rate that could possibly be accomplished. The PBR productivity assumptions will be scaled up according to the assumptions of the case-study. The values used are inside the range assumed by several studies in the scientific literature.

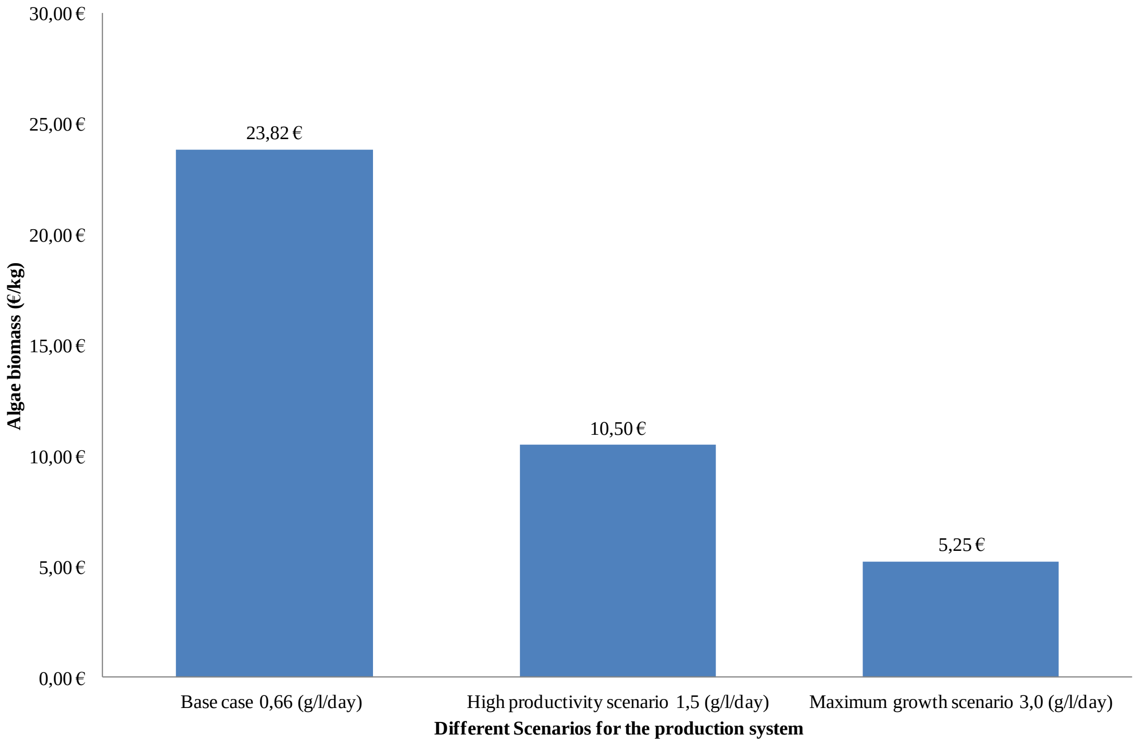


Figure 11 Production cost for different production scenarios

Figure 11 demonstrates that there is a certain possibility for significant development in microalgae biomass production economics, if a strain can be engineered to withstand a high growth rate. When compared to the other scenarios it is possible to identify a certain reduction in the final price of producing microalgae biomass. Comparing the different production scenarios is possible to identify a major reduction for the PBR systems. For maximum productivity scenario of the system, the reduction is exceptionally high, to values close to 5.25 €/kg, for the "high productivity scenario" the value decreases to 10.50 €/kg.

Cost plays a central role in process economics, making the minimization of CO_2 cost a top priority for all industries (Kadam & Sheehan 1996). A scenario is presented where a rigorously derived CO_2 recovery-cost model is available in the context of microalgae cultivation. Power-plant flue gas can serve as a source of CO_2 for microalgae cultivation. Figure 12 presents a scenario involving the growth of algae from a nearby power station and assumes that pure CO_2 is being delivered to the production system from a nearby power plant. The possibility of growing microalgae in PBR´s using wastewater high in nutrients (N & P) for the production of biomass is an option being developed for the future. Another scenario option is set assuming nutrients are delivered to the process using wastewater as a medium and source of nutrients for algae production.

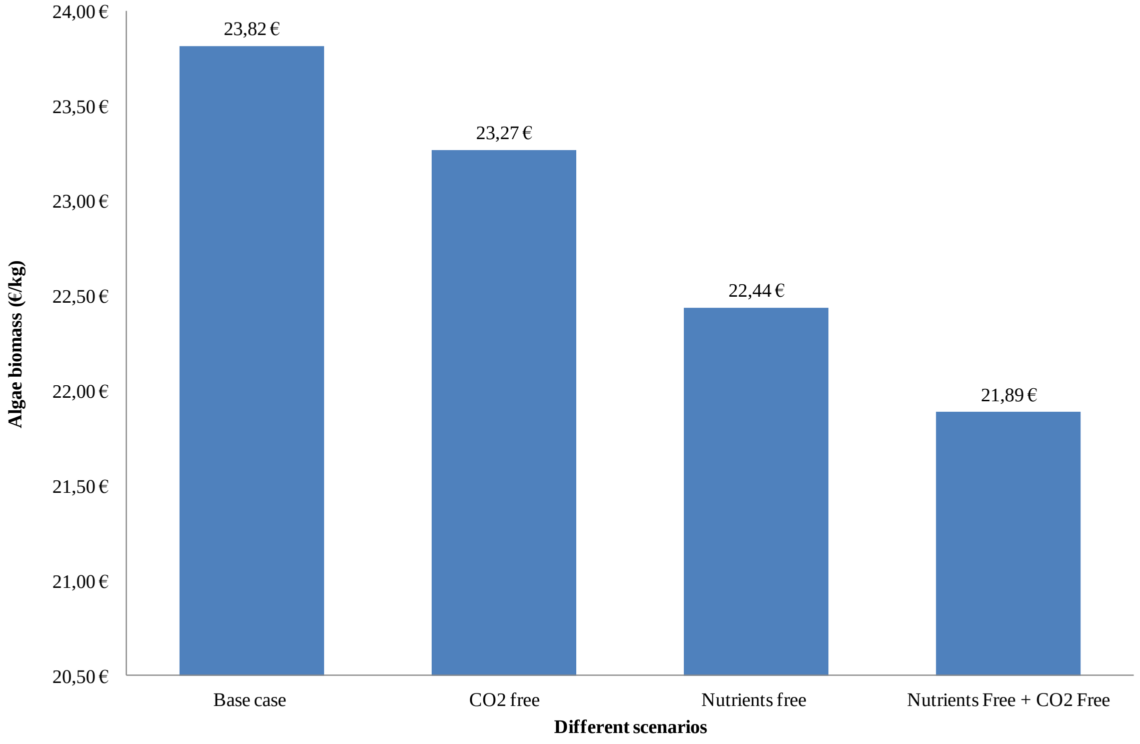


Figure 12 Different scenarios for the case study

The estimated cost of producing a kilogram of algae biomass with the use of the free addition of CO_2 is around 23.00 €/kg. The cost of production per kilogram is reduced to roughly 0.55 €/kg. An important aspect is that if flue gas is to be a CO_2 source, one task is the selection of viable algae strains for producing algae biomass assuming that little or no gas purification occurs. If the source of CO_2 is reasonably clean and concentrated, CO_2 fixation by the microalgae strain will be feasible and cost effective. The expected cost of producing a kilogram of algae biomass with the use of the free addition of nutrients is approximately 22.00 €/kg. It is possible to identify a cost reduction around 1.38 €/kg. Through a possibility of adding the two scenarios employed together, CO_2 and nutrients, both free, the final price was found to be roughly 22.00 €/kg, with a cost reduction of 1.93 €/kg generated in the system.

The approach of the following scenario is the scale-up of a photo-bioreactor, assuming three different scenarios (Figure 13). The first scenario is the base case, with a price about 24.00 €/kg. The second scenario, where a medium scale of the total number of

PBR is set, with a total volume of 150 m^3 and a large scale scenario, with a total volume of 300 m^3. In general, scale-up can be realized by increasing the tube length and/or the tube diameter.

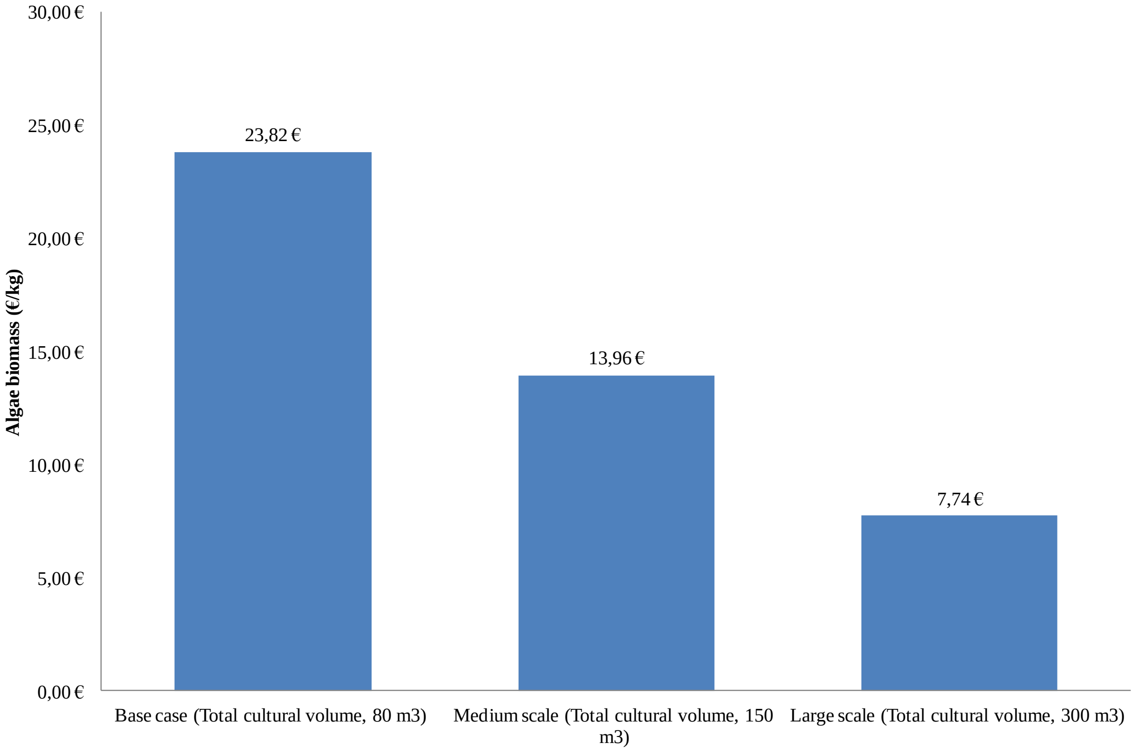


Figure 13 Different volume for the scenarios on the case study

Three different scenarios of microalgae biomass cultivation with different volumes were evaluated. Comparing the three different scenarios of large scale production, it is possible to identify some interesting results. For the large scale production system, a cost reduction of 16.08 €/kg is possible to accomplish, with a final price of biomass of approximately, 7.74 €/kg. For the medium scale scenario, the final price of microalgae biomass was 13.96 €/kg. The key problems with large scale production of microalgae biomass are restricted not only by the performance of the PBR´s, in which light penetration in dense cultures is a key bottleneck, but also by the characteristics of the organisms. The development of cost-effective, sustainable systems to produce microalgae on a large scale is a solution for the future of biotechnology.

5. CONCLUSIONS

Microalgae biomass production and scale up aspects seem relatively promising. It is particularly difficult to know precisely what investment will be required for scale up and what cost reductions can be achieved. A major conclusion from these analyses is that there is a big challenge and opportunity for finding alternatives to the PBR designs, given strain improvements and the lipid contents of the microalgae. The analysis in this work point to the need for finding highly productive organisms able to convert high levels of biomass. Algae based biofuels originating from microalgae biomass is an interesting option for the transportation system, although government subsidies play an important role in generating incentives to support the needed investment. The transformation process of biomass to biofuels is still relatively expensive.

The production costs for microalgae production of biomass are presently relatively high and new innovations are necessary to reduce the production costs. The advance of PBRs to increase the efficiency of the cultivation process might be a solution if the cost of these systems would go down and if they are developed for large scale production. Developments in both productivity and energy efficiency would be essential to significantly cut the cost of biomass production. The use of waste water for a prospective future nutrient shortage and rising nutrient prices, and utilizing CO_2 from flue gases could be extremely promising in their ability to significantly improve the sustainability of the industry from an economic perspective. CO_2 flue gases are an opportunity for increasing the profitability of the system even though it cannot withstand a business model.

The economics of algae biomass production are heavily reliant on the scale of operations. Through economies of scale, scaling up facilities can accomplish a minor production price/kilogram for the biomass generated within the system. However, scaling up microalgae biomass production facilities is still a challenge. Engineers still have to develop PBR´s cheap enough for large scale distribution. An important aspect is the price arising originally from the harvesting phase. It represents a difficult problem, since the properties of the microalgae used and its nutritional status, will define the strategy that can be used for harvesting. Harvesting costs represent an important cost addition to the power requirements of the process.

5.1. Opportunities and challenges

Microalgae are currently being cultivated commercially for nutritional products in a few small-to medium-scale production systems, with a production capacity of a few to several hundreds of tons of biomass yearly. On the opposite hand, the cultivation of microalgae for oil production, in particular, is not yet a commercial certainty and still requires relatively long-term R&D, over the next 30 years. This is due in part to the extremely high costs of generating a simple production system with a focus on bio-fuels relative to the achievement of high biomass productivity. At the moment, this presents an incredible opportunity, but also a significant challenge to the development and perfection of this particular type of biomass.

During the writing of this dissertation it was possible to find guidelines for an extensive understanding of why the development of this particular production is not yet offered. Table 16 shows a summary of some opportunities and challenges that are significant for the future development of bio-fuels and for a comprehensive understanding of why R&D is still a long-term answer for the problem.

Table 16 Opportunities and challenges to microalgae production

Cultivation	Opportunities	Challenges
Water	Water can be recycled via a renewed use of the cultivating media and through the utilization of nitrogen and phosphate contained in wastewater.	This practice hasn´t been established yet
Nutrients	Microalgae feedstock production can be integrated with wastewater[1]	Critical challenge that could fundamentally change the economics of algae fuel production
CO_2	Use microalgae to absorb greenhouse gas emissions from a coal-fired power plant	Land shortage around this specific industrial areas[2]
Energy	Area with high humidity, sunny weather, large unused area and with salty water	They use sunlight five times more efficiently than terrestrial plants, but it requires substantial area with high energy
Species	Develop ongoing strain selection and improvement for higher productivity, harvestability and biomass conversion[3]	Lack of experience how to grow them reproducibly or economically.
Contamination	Contamination with bacteria, protozoa or another species of algae is a serious problem for monospecific/axenic cultures of microalgae[4]	Decreasing contamination and Increasing microlgae Yields
Productivity	Starve algae from nitrogen increases lipid´s productivity[5]	Slow down growth yield and consenquently operation costs
Harvesting	Harvesting microalgae is extremelly difficult due to the small size of the algae, choosing the effecting harvesting process for a particular microagae can be difficult	One of the cost of production problems that holds algae back as a major biomass resource is an efficient cost-effective method of harvesting[6]
Lipid extraction	Opportunities to reduce costs of scaling up algal lipid extraction, some technologies are being developed	One of the challenges in utilizing microalgae to make biodiesel is the complexities of extracting the lipids using organic solvents followed by transesterification of the extracts to biodiesel[7]

Source: (Dalrymple et al., 2013)[1];(Pate et al. 2011)[2]; (Fraunhofer Institute for Interfacial Engineering, 2013)[3];(Lavens & Sorgeloos, 1996)[4];(Rösch, 2004)[5];(Lardon, Hélias, Sialve, Steyer, & Bernard, 2009)[6]; (Wahlen, Willis, & Seefeldt, 2011)[7]

5.2. Future research

To define the path of future work research, there is a brief review of the concepts which emerged during the critical thesis process. This chapter also briefly summarizes those ideas that has been considered interesting, but unfortunately were not followed during the time frame of this work. A detailed sensitivity analysis on the model should be performed to examine the impact of various changes in the process parameters such as the energy demand of the process and the CO_2 emissions savings. It is also necessary to perform detailed cost estimation for the complete algae wastewater treatment and bio-fuels production concept, including the upfront investment needed and a determination of which operating costs should be analyzed.

The idea of integrating LCA with economic analysis is interesting and has sufficient potential to undertake significant research work. Both environmental and economic impacts are highly relevant for understanding the overall sustainability of these systems. In order to achieve a better understanding of these systems, it is expected that future research will focus on developing a multi-objective optimization model combining economic and environmental impacts related to the development and implementation of a microalgae production system

6. REFERENCES

Acién, F. G., Fernández, J. M., Magán, J. J., & Molina, E. (2012). Production cost of a real microalgae production plant and strategies to reduce it. *Biotechnology advances*, *30*(6), 1344-53. Elsevier Inc. doi:10.1016/j.biotechadv.2012.02.005

Aguiar, R. (2006). *Avaliação do Recurso solar da Região do Algarve* (pp. 0-77).

Araujo, G. S., Matos, L. J. B. L., Gonçalves, L. R. B., Fernandes, F. A. N., & Farias, W. R. L. (2011). Bioprospecting for oil producing microalgal strains: evaluation of oil and biomass production for ten microalgal strains. *Bioresource technology*, *102*(8), 5248-50. doi:10.1016/j.biortech.2011.01.089

Batista, L. G. A. P., Sousa, I., & Raymundo, A. (2008). Microalgae in Novel Food Products. In K. N. Papadopoulos (Ed.), *Food Chemistry Research Developments*. 2008 Nova Science Publishers, Inc.

Becker, E. W. (1994). *Microalgae: biotechnology and microbiology*. (J. Baddiley, N. H. Carey, I. J. Higgins, & W. G. Potter, Eds.)*Small* (Vol. 10, p. 293). Cambridge University Press.

Becker, E. W. (2006). Micro-algae as a source of protein. *Biotechnology advances*, *25*(2), 207-10. doi:10.1016/j.biotechadv.2006.11.002

Bejan, A., & Moran, M. J. (1996). *Thermal Design and Optimization* (p. 542). John Wiley & Sons.

Benemann, J., Jarvis, E., Milbrant, A., & Ringer, M. (2011). Algae as a Feedstock for Biofuels.

Benemann, John R. (2008). Overview : Algae Oil to Biofuels (annotated presentation) Abstract – a short history of algae biofuels.

Benemann, J. R., & Oswald, W. J. (1994). Systems and economic analysis of microalgae ponds for conversion of CO2 to biomass. *NASA STI/Recon Technical Report N*, *95*, 19554.

Benemann, J.R., & Oswald, W. J. (1996). Systems and economic analysis of microalgae ponds for conversion of CO{sub 2} to biomass. Final report. doi:10.2172/493389

Bogle, D., & Fairweather, M. (2012). *22nd European Symposium on Computer Aided Process Engineering* (p. 1400). Elsevier.

Bosma, R., Spronsen, W. A., Tramper, J., & Wijffels, R. H. (2003). Ultrasound, a new separation technique to harvest microalgae. *Journal of Applied Phycology*, *15*(2/3), 143-153. Springer Netherlands. doi:10.1023/A:1023807011027

Brennan, L., & Owende, P. (2010). Biofuels from microalgae—A review of technologies for production, processing, and extractions of biofuels and co-products. *Renewable and Sustainable Energy Reviews*, *14*(2), 557-577. Elsevier Ltd. doi:10.1016/j.rser.2009.10.009

Bullis, K. (2012). Sapphire Energy Raises $144 Million for an Algae Farm | MIT Technology Review. Retrieved from

Bumbak, F., Cook, S., Zachleder, V., Hauser, S., & Kovar, K. (2011). Best practices in heterotrophic high-cell-density microalgal processes: achievements, potential and possible limitations. *Applied microbiology and biotechnology*, *91*(1), 31-46. doi:10.1007/s00253-011-3311-6

Carvalho, A. P., Meireles, L. A., & Malcata, F. X. (2006). Microalgal reactors: a review of enclosed system designs and performances. *Biotechnology progress*, *22*(6), 1490-506. doi:10.1021/bp060065r

Chaumont, D. (1993). Biotechnology of algal biomass production: a review of systems for outdoor mass culture. *Journal of Applied Phycology*, *5*(6), 593-604. doi:10.1007/BF02184638

Chen, P., Min, M., Chen, Y., & Wang, L. (2010). Review of biological and engineering aspects of algae to fuels approach. ... *Engineering*, *2*(4). doi:10.3965/j.issn.1934-6344.2009.04.001-030

Chisti, Y. (2007). Biodiesel from microalgae. *Biotechnology advances*, *25*(3), 294-306. doi:10.1016/j.biotechadv.2007.02.001

Chisti, Y., & Yan, J. (2011). Energy from algae: Current status and future trends. *Applied Energy*, *88*(10), 3277-3279. Elsevier Ltd. doi:10.1016/j.apenergy.2011.04.038

Christenson, L., & Sims, R. (2011). Production and harvesting of microalgae for wastewater treatment, biofuels, and bioproducts. *Biotechnology advances*, *29*(6), 686-702. doi:10.1016/j.biotechadv.2011.05.015

Clarke, A. R. (1995). Photosynthesis fifth edition. *Biochemical Education*, *23*(1), 47. doi:10.1016/0307-4412(95)90203-1

Collet, P., Hélias, A., Lardon, L., Ras, M., Goy, R.-A., & Steyer, J.-P. (2009). Life-cycle assessment of microalgae culture coupled to biogas production. *Bioresource technology*, *102*(1), 207-14. Elsevier Ltd. doi:10.1016/j.biortech.2010.06.154

Dalrymple, O. K., Halfhide, T., Udom, I., Gilles, B., Wolan, J., Zhang, Q., & Ergas, S. (2013). Wastewater use in algae production for generation of renewable resources: a review and preliminary results. *Aquatic biosystems*, *9*(1), 2. BioMed Central Ltd. doi:10.1186/2046-9063-9-2

Darzins, Philip Pienkos, L. E. (2010). *Current Status and Potential for Algal Biofuels Production*.

Davis, R., Aden, A., & Pienkos, P. T. (2011). Techno-economic analysis of autotrophic microalgae for fuel production. *Applied Energy*, *88*(10), 3524-3531. Elsevier Ltd. doi:10.1016/j.apenergy.2011.04.018

Dinh, L. T. T., Guo, Y., & Mannan, M. S. (2009). Sustainability Evaluation of Biodiesel Production Using, *28*(1). doi:10.1002/ep

Dragone, G., Fernandes, B., Vicente, A. A., & Teixeira, J. A. (2010). Third generation biofuels from microalgae, 1355-1366.

Drapcho, C., Nhuan, N., & Walker, T. (2008). *Biofuels Engineering Process Technology*. (I. The McGraw-Hill Companies, Ed.).

Emhjellen, K., Emhjellen, M., & Osmundsen, P. (2002). Investment cost estimates and investment decisions. *Energy Policy*, *30*(2), 91-96. doi:10.1016/S0301-4215(01)00065-9

Ereev, S., & Patel, M. (2011). *Recommended methodology and tool for cost estimates at micro level for new technologies*. Utrecht.

Ereev, S. Y., & Patel, M. K. (2012). Standardized cost estimation for new technologies (SCENT) - methodology and tool, *9*(1).

Fehrenbacker, K. (2012). The long, long (long) road for algae fuel — Tech News and Analysis. Retrieved from

Flickinger, M. C. (2009). *Encyclopedia of Industrial Biotechnology*. Hoboken, NJ, USA: John Wiley & Sons, Inc. doi:10.1002/9780470054581.eib418

Fraunhofer. (2011). *Microalgae – a sustainable resource for valuable compounds and energy production* (p. 8). Stuggart.

Fraunhofer Institute for Interfacial Engineering. (n.d.). Use of filtrate water from digestion for the cultivation of microalgae - Fraunhofer Institute for Interfacial Engineering and Biotechnology IGB. Retrieved from

Greenwell, H. C., Laurens, L. M. L., Shields, R. J., Lovitt, R. W., & Flynn, K. J. (2010). Placing microalgae on the biofuels priority list: a review of the technological challenges. *Journal of the Royal Society, Interface / the Royal Society*, *7*(46), 703-26. doi:10.1098/rsif.2009.0322

Grima, E. M., & Belarbi, E.-H. (2003). Recovery of microalgal biomass and metabolites: process options and economics. *Biotechnology ...*, *20*(7-8), 491-515.

Hannon, M., Gimpel, J., Tran, M., Rasala, B., & Mayfield, S. (2010). Biofuels from algae: challenges and potential. *Biofuels*, *1*(5), 763-784.

Hans Wolkers, Maria Barbosa, Dorinde M.M. Kleinegris, Rouke Bosma, R. H. W. (2011). *Microalgae: the green gold of the future? Large-scale sustainable cultivation of microalgae for the production of bulk commodities* (p. 32). Wageningen. Retrieved from www.algae.wur.nl

Heasman, M., Diemar, J., O'connor, W., Sushames, T., & Foulkes, L. (2000). Development of extended shelf-life microalgae concentrate diets harvested by centrifugation for bivalve molluscs - a summary. *Aquaculture Research*, *31*(8-9), 637-659. doi:10.1046/j.1365-2109.2000.318492.x

Heinzle, E., Biwer, A. P., & Cooney, C. L. (2007). *Development of Sustainable Bioprocesses: Modeling and Assessment (Google eBook)* (Vol. 6, p. 316). John Wiley & Sons.

Huntley, M. E., & Redalje, D. G. (2006). CO2 Mitigation and Renewable Oil from Photosynthetic Microbes: A New Appraisal. *Mitigation and Adaptation Strategies for Global Change*, *12*(4), 573-608. doi:10.1007/s11027-006-7304-1

Jelen, F. C., Black, J. H., & Engineers, A. A. of C. (1983). *Cost and optimization engineering*.

Jorquera, O., Kiperstok, A., Sales, E. a, Embiruçu, M., & Ghirardi, M. L. (2010). Comparative energy life-cycle analyses of microalgal biomass production in open ponds and photobioreactors. *Bioresource technology*, *101*(4), 1406-13. Elsevier Ltd. doi:10.1016/j.biortech.2009.09.038

Kirrolia, A., Bishnoi, N. R., & Singh, R. (2013). Microalgae as a boon for sustainable energy production and its future research & development aspects. *Renewable and Sustainable Energy Reviews*, *20*, 642-656. Elsevier. doi:10.1016/j.rser.2012.12.003

Kleivdal, H., Nordvik, S. M., Mork-Pedersen, T., & Haugland, A. (2012). *CO2 to Bio Microalgae as an omega-3 rich feedstock -integrating CO2 sequestration and aquafeed production* (p. 119). Mongstad.

Kumar, A., Ergas, S., Yuan, X., Sahu, A., Zhang, Q., Dewulf, J., Malcata, F. X., et al. (2010). Enhanced CO(2) fixation and biofuel production via microalgae: recent developments and future directions. *Trends in biotechnology*, *28*(7), 371-80. Elsevier Ltd. doi:10.1016/j.tibtech.2010.04.004

Lardon, L., Hélias, A., Sialve, B., Steyer, J.-P., & Bernard, O. (2009). Life-Cycle Assessment of Biodiesel Production from Microalgae. *Environmental Science & Technology*, *43*(17), 6475-6481. American Chemical Society. doi:10.1021/es900705j

Lavens, & Sorgeloos. (1996). Manual on the Production and Use of Live Food Aquaculture. *Food and Agriculture Organization of the United Nations*. Retrieved from

Lundquist, T. J., Woertz, I. C., Quinn, N. W. T., & Benemann, J. R. (2010). *A Realistic Technology and Engineering Assessment of Algae Biofuel Production* (p. 178). Berkeley, California.

Macías-Sánchez, M. D., Fernandez-Sevilla, J. M., Fernández, F. G. A., García, M. C. C., & Grima, E. M. (2010). Supercritical fluid extraction of carotenoids from Scenedesmus almeriensis. *Food Chemistry*, *123*(3), 928-935. doi:10.1016/j.foodchem.2010.04.076

McGinn, P. J., Dickinson, K. E., Bhatti, S., Frigon, J.-C., Guiot, S. R., & O'Leary, S. J. B. (2011). Integration of microalgae cultivation with industrial waste remediation for biofuel and bioenergy production: opportunities and limitations. *Photosynthesis research*, *109*(1-3), 231-47. doi:10.1007/s11120-011-9638-0

Moheimani, N. R., & Borowitzka, M. A. (2007). Limits to productivity of the alga Pleurochrysis carterae (Haptophyta) grown in outdoor raceway ponds. *Biotechnology and bioengineering*, *96*(1), 27-36. doi:10.1002/bit.21169

Molina Grima, E., Belarbi, E.-H., Acién Fernández, F. ., Robles Medina, A., & Chisti, Y. (2003). Recovery of microalgal biomass and metabolites: process options and economics. *Biotechnology Advances*, *20*(7-8), 491-515. doi:10.1016/S0734-9750(02)00050-2

Muñoz, R., & Guieysse, B. (2006). Algal-bacterial processes for the treatment of hazardous contaminants: a review. *Water research*, *40*(15), 2799-815. doi:10.1016/j.watres.2006.06.011

Norsker, N.-H., Barbosa, M. J., Vermuë, M. H., & Wijffels, R. H. (2010). Microalgal production--a close look at the economics. *Biotechnology advances*, *29*(1), 24-7. doi:10.1016/j.biotechadv.2010.08.005

Nurdogan, Y., & Oswald, W. (1996). Tube settling of high-rate pond algae. *Water Science and Technology*, *33*(7), 229-241. doi:10.1016/0273-1223(96)00358-7

Oliveira, P. (2002). *Considerações sobre o clima do Algarve* (pp. 1-6).

Pienkos, P. T., & Darzins, A. (2009). of microalgal-derived biofuels †, 431-440. doi:10.1002/bbb

Priyadarshani, I., & Rath, B. (2012). Commercial and industrial applications of micro algae – A review, *3*(4), 89-100.

Pulz. (2001). Photobioreactors: production systems for phototrophic microorganisms. *Applied Microbiology and Biotechnology*, *57*(3), 287-293. doi:10.1007/s002530100702

Pulz, O., & Gross, W. (2004). Valuable products from biotechnology of microalgae. *Applied microbiology and biotechnology*, *65*(6), 635-48. doi:10.1007/s00253-004-1647-x

Renaud, T., & Stroud, R. S. (2011). *Due Diligence and Valuation Report Table of Contents* (pp. 1-28).

Ribeiro, L. A., & Silva, P. P. (2013). Surveying techno-economic indicators of microalgae biofuel technologies. *Renewable and Sustainable Energy Reviews*, *25*(null), 89-96. doi:10.1016/j.rser.2013.03.032

Richardson, J., Outlaw, J., & Allison, M. (2010). The economics of microalgae oil, *13*(2), 119-130.

Richmond, A. (1992). Open systems for the mass production of photoautotrophic microalgae outdoors: physiological principles. *Journal of Applied Phycology*, *4*(3), 281-286. doi:10.1007/BF02161213

Rösch, C., Skarka, J., & Patyk, A. (2009). MICROALGAE – OPPORTUNITIES AND CHALLENGES OF AN INNOVATIVE ENERGY SOURCE, *0049*(July), 1-7.

Rösch, P. (2004). Challenges and Perspectives of Microalgae Production - 2012. Retrieved from

Sanchez Miron, A., Ceron Garcia, M. C., Contreras Gomez, A., Garcia Camacho, F., Molina Grima, E., & Chisti, Y. (2003). Shear stress tolerance and biochemical characterization of Phaeodactylum tricornutum in quasi steady-state continuous culture in outdoor photobioreactors. *Biochemical engineering journal*, *16*(3), 287-297. Elsevier.

Sathish, A., Sims, R., & Wood, B. (2012). Biodiesel Production from Mixed Culture Algae Via a Wet Lipid Extraction Procedure.

Schenk, P. M., Thomas-Hall, S. R., Stephens, E., Marx, U. C., Mussgnug, J. H., Posten, C., Kruse, O., et al. (2008). Second Generation Biofuels: High-Efficiency Microalgae for Biodiesel Production. *BioEnergy Research*, *1*(1), 20-43. doi:10.1007/s12155-008-9008-8

Sheehan, J., Dunahay, T., Benemann, J., & Roessler, P. (1998). *A look back at the US department of energy's aquatic species program: biodiesel from algae*.

Shelef, G., & Sukenik, A. (1984). Microalgae Harvesting and Processing : A Literature Review, (0).

Singh, A., Nigam, P. S., & Murphy, J. D. (2011). Mechanism and challenges in commercialisation of algal biofuels. *Bioresource technology*, *102*(1), 26-34. doi:10.1016/j.biortech.2010.06.057

Singh, A., & Olsen, S. I. (2011). A critical review of biochemical conversion, sustainability and life cycle assessment of algal biofuels. *Applied Energy*, *88*(10), 3548-3555. Elsevier Ltd. doi:10.1016/j.apenergy.2010.12.012

Singh, J., & Gu, S. (2010). Commercialization potential of microalgae for biofuels production. *Renewable and Sustainable Energy Reviews*, *14*(9), 2596-2610. Elsevier Ltd. doi:10.1016/j.rser.2010.06.014

Singh, N. K., & Dhar, D. W. (2011). Microalgae as second generation biofuel. A review. *Agronomy for Sustainable Development*, *31*(4), 605-629. doi:10.1007/s13593-011-0018-0

Spolaore, P., Joannis-Cassan, C., Duran, E., & Isambert, A. (2006). Commercial applications of microalgae. *Journal of bioscience and bioengineering*, *101*(2), 87-96. doi:10.1263/jbb.101.87

Sun, A., Davis, R., Starbuck, M., Ben-Amotz, A., Pate, R., & Pienkos, P. T. (2011). Comparative cost analysis of algal oil production for biofuels. *Energy*, *36*(8), 5169-5179. doi:10.1016/j.energy.2011.06.020

Surendhiran, D., & Vijay, M. (2012). Microalgal Biodiesel - A Comprehensive Review on the Potential and Alternative Biofuel, *2*(11), 71-82.

Sánchez, J. F., Fernández, J. M., Acién, F. G., Rueda, a., Pérez-Parra, J., & Molina, E. (2008). Influence of culture conditions on the productivity and lutein content of the new strain Scenedesmus almeriensis. *Process Biochemistry*, *43*(4), 398-405. doi:10.1016/j.procbio.2008.01.004

Tapie, P., & Bernard, A. (1988). Microalgae production: technical and economic evaluations. *Biotechnology and bioengineering*, *32*(7), 873-85. doi:10.1002/bit.260320705

Terry, K. L., & Raymond, L. P. (1985). System design for the autotrophic production of microalgae. *Enzyme and Microbial Technology*, *7*(10), 474-487. doi:10.1016/0141-0229(85)90148-6

Torzillo, G., Pushparaj, B., Bocci, F., Balloni, W., Materassi, R., & Florenzano, G. (1986). Production of Spirulina biomass in closed photobioreactors. *Biomass*, *11*(1), 61-74. doi:10.1016/0144-4565(86)90021-1

Viktor Andersson, Sarah Broberg, R. H. (2011). *Integrated Algae Cultivation for Biofuels Production in Industrial Clusters* (p. 92). Linkoping.

Wahlen, B. D., Willis, R. M., & Seefeldt, L. C. (2011). Biodiesel production by simultaneous extraction and conversion of total lipids from microalgae, cyanobacteria, and wild mixed-cultures. *Bioresource technology*, *102*(3), 2724-30. doi:10.1016/j.biortech.2010.11.026

Walker, T. L., Purton, S., Becker, D. K., & Collet, C. (2005). Microalgae as bioreactors. *Plant cell reports*, *24*(11), 629-41. doi:10.1007/s00299-005-0004-6

Weissman, J. C., Goebel, R. P., & Benemann, J. R. (1988). Photobioreactor design: Mixing, carbon utilization, and oxygen accumulation. *Biotechnology and bioengineering*, *31*(4), 336-44. doi:10.1002/bit.260310409

Widjaja, A., Chien, C.-C., & Ju, Y.-H. (2009). Study of increasing lipid production from fresh water microalgae Chlorella vulgaris. *Journal of the Taiwan Institute of Chemical Engineers*, *40*(1), 13-20. doi:10.1016/j.jtice.2008.07.007

Williams, P. J. L. B., & Laurens, L. M. L. (2010). Microalgae as biodiesel & biomass feedstocks: Review & analysis of the biochemistry, energetics & economics. *Energy & Environmental Science*, *3*(5), 554. doi:10.1039/b924978h

Xu, D., Slade, R., Bauen, A., Acien, F. G., Queguineur, B., & Ratcliff, J. (2011). *Algae and aquatic biomass for a sustainable production of 2nd generation biofuels*. *cssc.eu* (p. 120).

Zamalloa, C., Vulsteke, E., Albrecht, J., & Verstraete, W. (2011). The techno-economic potential of renewable energy through the anaerobic digestion of microalgae. *Bioresource technology*, *102*(2), 1149-58. doi:10.1016/j.biortech.2010.09.017

Zugarramurdi, A., Parin, M. A., & Lupin, H. M. (1995). *Economic Engineering Applied to the Fishery Industry*. Retrieved from http://books.google.pt/books/about/Economic_Engineering_Applied_to_the_Fish.html?id=a4lUTm1-f9kC&pgis=1

7. APPENDIX A

Table 17 Direct production costs for the case study

Item	Raw materials	€/unit	Nº of units	Total cost	Source	Notes
1	Fertilizers (kg)	0,55 €	43560	23.958,00 €	Molina Grima et al., 2003	Takes 2.5 kg of medium to produce 1 kg of algal biomass in photobioreactor
2	Carbon Dioxide (kg)	0,30 €	31885,92	9.565,78 €	Acíen et al., 2012	Takes 1.83 kg of CO_2 to produce 1 kg of biomass
Item	**Utilities**					
4	Water (€/m3)	0,10 €	19360	1.936,00 €	Calculated in water requirements	Section 3.6
5	Power consumption (kWh)	0,10 €	88604,42	8.860,44 €	Calculated in Energy requirements	Section 3.5
Item	**Labor and others**					
6	Labor	27.300,00 €	6	163.800,00 €	Wages and labour costs - Statistics Explained	Assuming cost of hour 12.10€ and 40 hours week
7	Supervision (at 0.2 labor)	32.760,00 €	0,2	6.552,00 €	(Acíen et al., 2012; Ereev & Patel, 2012; Frioui & Oumeddour, 2010; Silla, 2003)	
8	Payroll charges (at 0.25 labor+supervision)	42.588,00 €	0,25	10.647,00 €		
9	Maintenance (at 0.04 Major Equipment Cost)	28.008,38 €	0,04	1.120,34 €		
10	General plant overhead (at 0.55 (labor+supervision+maintenance)	99.549,45 €	0,55	54.752,20 €		
11	Contingency (at 0.05 items 1-7)	10.733,61 €	0,05	536,68 €		
12	Marketing (at 0.05 items 1-11)	14.086,42 €	0,05	704,32 €		
Total raw materials				**33.523,78 €**		
Total utilities				**10.796,44 €**		
Total labor and others				**238.112,53 €**		

Table 18 Major equipment scaled up production cost

Production equipment	Cost in Euro	Scaling Factor	Capacity	Unit	Share (%)
Photobioreactors	337.600,00 €	100	100	m^3	35,58%
Culture medium preparation unit	42.703,75 €	1,27	26,61	m^3/h	4,50%
Carbon dioxide supply station	2.100,00 €	2,1	9,6	kg/h	0,22%
Centrifuge	232.410,00 €	1,27	3,98	m^3/h	24,49%
Harvest feed pump	2.300,00 €	2,3	16,6	m^3/h	0,24%
Harvest broth storage tank	44.213,78 €	1,27	80	m^3	4,66%
Culture medium feed pump	1.080,00 €	0,18	1,73	m^3/h	0,11%
Biomass silos	3.302,00 €	1,27	0,09	m^3	0,35%
Sterilization process	34.500,00 €	2,3	5.3	m^3/h	3,64%
Total	700.209,53 €				

Table 19 Fixed capital estimated for the case study

Item	Detail	Factor	Cost
1	Major equipment	1,00	700.209,53 €
2	Intallation costs	0,20	140.041,91 €
3	Instrumentation and control	0,15	105.031,43 €
4	Piping	0,18	126.037,72 €
5	Electrical	0,10	70.020,95 €
6	Buildings	0,23	161.048,19 €
7	Yard improvements	0,10	70.020,95 €
8	Service facilities	0,20	140.041,91 €
9	Land	0,06	42.012,57 €
10	Engineering and supervision	0,30	210.062,86 €
11	Construction expenses	0,05	77.723,26 €
12	Contractor´s fee	0,03	46.633,95 €
13	Contingency	0,07	108.812,56 €
Total fixed capital			1.997.697,79 €
Item			
1	Lifetime	15,00	
2	Depreciation		133.179,85 €
3	Property tax (at 0.01 depreciation)	0,01	1.331,80 €
4	Purchase tax (at 0,16 of items 1-12/10)		19.018,81 €
5	Insurance (at 0.006 depreciation)	0,01	799,08 €
Total fixed capital per annun			154.329,54 €