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1. Introduction

1.1 Objective and structure of this report

Economic analysis is a powerful tool that can be used to both evaluate the production cost of algae biofuels and help identify the major factors which contribute most to the production cost – thereby helping to focus future engineering research. This report examines how economic assessment has been used to estimate the future cost of transport fuels produced from algal biomass. The specific objectives of this report are:

1. To review the current status of economic analysis of algae derived biofuels that are available in the academic literature; the strengths and weakness of these studies are assessed in detail.
2. Provide an illustrative analysis of the current and projected costs of producing algal biomass in raceway ponds and photo-bioreactors.

The report is structured as follows:

- Chapter 1: Describes the objectives and structure of the report and introduced the AquaFUELs project of which this research is part.
- Chapter 2: Presents an analysis of algae economic assessments that are available in the academic literature. Strengths and weaknesses are identified and the figures are critiqued, this critique draws on both literature sources and data gathered from expert stakeholders.
- Chapter 3: Presents an illustrative economic analysis of PBR and raceway pond scenarios.
- Chapter 4: Reviews issues affecting the economic performance of algae discussed at the 2010 Aquafuels roundtable on the state of the art and future perspectives for algae biofuels .
- Chapter 5: Conclusions and recommendations.

1.2 The Aquafuels project

The work presented in this report was undertaken within the context of an EU sponsored project: Aquafuels (AquaFUELs, 2010). This project aims to bring together and co-ordinate existing knowledge, and to establish the state of the art for research, technological development and demonstration activities regarding the exploitation of algal biomass for 2nd generation biofuels production. A secondary objective of the project is to put robust and credible information about algae into the public domain, and thereby counter some of the more extravagant claims that have been expressed in the media.

2. **Review of Economic Assessments of micro-algae production systems**

This chapter describes and reviews recent economic assessments of algae biofuels production. It reviews the main features of the studies: choice of methodology, key input variables, and the way in which costs are allocated to products and co-products. A discussion of each of these input factors is provided based on discussion with stakeholders. The stakeholders consulted are listed in Annex 1.

Despite strong interest in algae for biofuels, it should be noted that no industrial scale process yet exists. Consequently, all available assessments are to a certain extent hypothetical. Nevertheless, several economic assessments have been recently completed, using estimates based on data extrapolated from laboratory scale pilots systems and previous literature.

There are five recent studies that we are including in this literature review, described in **Table 2.1.** These studies are representative of the most up to date economic analysis of algae biofuels. It should be noted that the majority of these studies describe open/raceway pond systems.

Table 2.1: Recent economic studies on algae derived fuels.

Author	**Year**	**Description/Abstract**
1. (Lundquist, et al., 2010)	2010	*This report assesses the economics of microalgae biofuels production through an analysis of five production scenarios. These scenarios, are based on technologies that currently exist or are expected to become available in the near term, including raceway ponds for microalgae cultivation, bioflocculation for algae harvesting, and hexane for extraction of algae oil. Process flow diagrams, facility site layouts, and estimates for the capital and operations costs of each case were developed de novo. This provides an initial assessment of the US and California resource potential for microalgae biofuels, and recommends specific R&D efforts to advance the feasibility of large-scale algae biofuel production.*
2. (Stephens, et al., 2010)	2010	*This study is trying to evaluate claims and provide an accurate analysis of the potential of microalgae biofuel system. The industrial feasibility studies and sensitivity analysis are based on peer-reviewed data and industrial expertise. Given that Microalgae biofuel research is still young and Its development still in flux, Author anticipate that the stringent assessment of the technology's economic potential will assist R&D investment and policy development in the area going forward.*
3. (Darzins, et al., 2010)	2010	*This study is part of IEA Task 39 projects; IEA Task 39 is to commission state-of-the-art reports on some of the most important relevant clean energy, liquid biofuels technology topics. This report seeks to examine the technical and economic feasibility of generating algal biomass for the production of liquid biofuels.*
4. (Richardson, et al., 2010)	2010	*A Monte Carlo simulation model for a commercial-scale microalgae farm in the US desert Southwest was developed and used to compare costs of*

		producing algal oil with two levels of technology. Ranges of input and output coefficients in the microalgae literature were used to simulate a farm using conventional wisdom regarding production and extraction. 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. The costs using the test farm's coefficients ranged from $0.15 to $0.45/pound, with a mean of $0.25 (with by-product credits).
5. (Zamalloa, et al., 2011)	2010	*Production of mixed culture algae in raceway ponds on non-agricultural sites. The potential of straightforward biomethanation, which includes pre-concentration of microalgae and utilization of a high rate anaerobic reactor was examined based on the premises of achievable up-concentration from 0.2–0.6 kg/m3 to 20–60 kg dry matter (DM)/m3 and an effective bio-methanation of the concentrate at a loading rate of 20 kg DM /m3/d. The costs of biomass available for bio-methanation under such conditions were calculated to be in the range of €86–€124 /tonDM. The levelized cost of energy by means of the process line ''algae biomass – biogas – total energy module" would be in the order of €0.170–0.087 /kWh, taking into account a carbon credit of about €30 /tonCO2(eq).*

2.1 Methodologies

The methodologies used in the reviewed economic assessments are listed in **Table 2.2** Most of the studies have applied the techno-economic method to evaluate the costs of algal bio-fuel production. Methods for economic assessment are discussed further in the following chapter.

Table 2.2: Methodologies applied on the existing economic assessments

Studies	Methodology
Richardson (2010)	*Monte Carlo simulation*
Zamalloa (2011)	*Techno-economic Assessment with Levelised cost of energy (LCOE)*
Darzins (2010)	*Techno-economic Assessment with Process Flow Diagrams methodology*
Stephens (2010)	*Techno-economic Assessment with Process Flow Diagrams methodology*
Lundquist (2010)	*Techno-economic Assessment with Process Flow Diagrams methodology*

2.2 Consideration of co-products and co-services

The studies consider different treatments of co-products, such as animal feed or high value product, or co-service (wastewater treatment) from algae biomass production (see **Table 2.3**) Lundquist (2010), for example, shows how the choice of co-service (wastewater treatment) could have a major impact in the final cost of biofuel production, while Stephens et.al. (2010) demonstrate the potential importance of high value co-product as a production strategy to offset the cost of biofuel production. More generally, numerous of previous assessments of biofuels have shown how important allocation calculations are on the final outcome.

Table 2.3: Allocation strategies from existing studies

Studies	Allocation strategies
Richardson (2010)	Animal feed
Zamalloa (2011)	Credits for heat and power generation
Darzins (2010)	Assumed certain values with the protein
Stephens (2010)	High value product, beta-carotene
Lundquist (2010)	Credit for wastewater treatment

2.3 Sources of data

There is significant variation in the parameter values used in the studies. The majority are based on pilot or lab scale values. The most frequently cited papers is by Benemann (1996), however some assumptions contained in this paper go back to the mid 1970's . One of major criticisms of the existing studies, therefore is the limited number of sources of data, and the lack of critical thinking about how reliable the sources and assumptions are. Again, it is necessary to emphasize the hypothetical nature of the current work.

2.4 Biomass productivity

Estimates for the productivity of algae are compared in **Table 2.4**. These estimates illustrate the range of optimism about possible micro-algae growth rates, and describe a range from 20-50 g/m^2/day with an average of 30 g/m^2/day.

Table 2.4: Algae biomass productivity assumptions used in Economic studies

Microalgae Biomass Productivity	**g/m^2/day**[1]	
Richardson (2010)	22~25	25g/m^2/day (data collected from literature); 22g/m^2/day (data collected from pilot testing system)
Zamalloa (2011)	20~30	3 cases had been assumed: 20g/m^2/day,25g/m^2/day,30g/m^2/day
Darzins (2010)	20	10~60 g/m^2/day for sensitivity analysis
Stephens (2010)	20~50	20g/m^2/day for the base case; 50g/m^2/day for the projected case
Lundquist (2010)	22	Combined with waste water treatment

1 All the estimates have been normalized to area basis (g/ m^2/day).

There is a general consensus among the stakeholders questioned that algae growth rates in terms of biomass productivity are too optimistic, and that they do not take into account the losses that would occur with scale up the process. In the open raceways, it is expected photosynthesis efficiency would not be higher than 1~2%, whereas, in photo-bioreactors (PBRs) efficiency may reach 4~5% under optimal conditions. Stakeholders also noted that biomass productivity values should be based on the yearly average productivity. It should be stressed that this is not equivalent to the mean productivity on a summer's day.

2.5 System availability and production days

Most of existing studies assumed that production can be all year round, however, depending on the location there may be several months of the year that are not suitable for harvesting as the temperature inhibits growth. Systems may also need to stop operation for maintenance and system cleaning on a periodic basis.

Table 2.5: System operation days assumptions used in economic studies

Production days	Days	Comment
Richardson (2010)	300~365	300 (data collected from literature, assumed two months are not suitable for production based on temperature); 365 (data collected from pilot testing system)
Zamalloa (2011)	330	330 days in the scenarios
Darzins (2010)	340	
Stephens (2010)	330	
Lundquist (2010)	300~365	For the case with wastewater treatment, system will be operated year round; for the case with the emphasis on biofuel production, system will be operated 10 month a year.

2.6 CO_2 usage

The studies assumed that producing 1 kg dry algal biomass requires 1.83-2.00kg CO_2, as shown in **Table 2.6**. The 1.83kg value, however comes from the carbon content of the algae biomass. In reality, CO_2 usage will several times higher. For example, in open raceways the CO_2 fixation efficiency is less than 10%. For thin layer cultivation the CO_2 efficiency is roughly 35%. In closed tubular photobioreactors (PBRs) the CO_2 efficiency may be up to 50%. Only by using advanced control strategies might the CO_2 efficiency be increased up to 90%. Considerable cost, therefore, is associated with providing CO2 that is not used by the algae.

Table 2.6: CO_2 assumptions used in economic studies

CO2 usage	kg/kg biomass	
Richardson (2010)	1.83	kg CO2 per kg of biomass produced
Zamalloa (2011)	NA	Assume CO2 is free
Darzins (2010)	2.00	kg CO2 per kg of biomass produced
Stephens (2010)	1.83	Biomass yield is 70 ton/ha/year, require 128 ton CO2/Ha/year
Lundquist (2010)	1.83	

A complicating factor is that it is generally not permissible to expulse CO_2 in large amounts at ground level. Managing large amounts of flue gases that are not efficiently used (low CO_2 absorption) could also have a negative effect on the energy balance of the system. It may also be restricted for health and environmental reasons.

2.7 Medium costs

The cost of culture medium is mainly a function of fertilizers. Costs can be reduced by re-circulating the culture medium but in this case the costs associated with medium conditioning must be included. Only the use of wastewater can reduce significantly the cost of culture medium. In this case the nitrate in the water is usually considered to be free (it only being necessary to pay for any additional nutrients required)**.** Depending on the location, water may also pose a substantial cost.

2.8 Labor cost

Labor is a function of culture volume, although there is variation between different cultivation systems. Describing labour cost in terms of the system area basis is perhaps easiest to understand, shown in **Table 2.7**. Project stakeholder considered that ~18 people for 100 ha open pond system would be reasonable. This estimate is based on the Lundquist et.al. (2010). For a PBR system this figure would have to doubled as the greater complexity and the need for maintenance will require more people.

Table 2.7: Labor cost assumptions used in economic studies

Labour (Working capital)	**people / ha**	
Richardson (2010)	0.03	Include administrative and operations personnel, totally 13 people in 400 ha area
Zamalloa (2011)	NA	Evaluated on cost per ha basis
Darzins (2010)	NA	Evaluated on cost per ha basis
Stephens (2010)	0.06	30 for 500 ha
Lundquist (2010)	0.14~0.18	18 for 100 ha, 4 for administrative people, 14 for operation;56 for 400ha, 4 for administrative, 52 for operation

2.9 Cost of final product

The cost of algae derived fuels derived from existing studies is shown in **Table 2.8.** It can be seen that co-product from residual algal biomass are an important source of revenue to achieve algal biofuels cost targets. A raceway pond system may not provide the controlled conditions required for high grade pharmaceutical products, however, using the residual algal biomass as an animal feed could improve the economic performance of algae derived fuels production. Alternatively, the residual biomass could be feed into anaerobic digester to produce methane for power generation.

In contrast, wastewater treatment alone might make raceway production of algal oil economical. Figures from Lundquist (2010) show that a wastewater treatment credit could reduce the cost of biofuel production significantly to around 28$/barrel. This figure assumes that large amount of nutrients would be supplied by wastewater. Yet Lundquist (2010) also argues that high value co-product market would likely become saturated before significant biofuel quantities were produced. He also comments that even with such advances (e.g. wastewater treatment credit) the resource potential of microalgae biofuels will be modest due to the lack of sites having all the required resource, such as sunshine, CO_2 and wastewater.

Table 2.8: Summary of cost of algal derived fuels from existing studies

Studies	**Cost of product (without co-product/ co-service)**			**Cost of product (with co-product/co-service)**	
	Main product	**Cost[5]**		**Co-product/Co service**	**Cost[5]**
(Richardson, et al., 2010)	Algal oil (base case)	3.18€/kg algal oil		Animal feed[1]	2.68€/kg algal oil
	Algal oil (Alternative case)	0.63 €/kg algal oil		Animal feed[1]	0.41 €/kg algal oil
(Zamalloa, et al., 2011)	Algal biomass	0.1239 €/kg biomass		Electricity[2]	0.17€/kWh
	Algal biomass	0.1006 €/kg biomass		Electricity[2]	0.113€/kWh
	Algal biomass	0.0857 €/kg biomass		Electricity[2]	0.087€/kWh
(Darzins, et al., 2010)	Algal 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
	Algal biodiesel (Australia)	Best scenario[3]	0.48 €/L	Animal feed	225 €/ton
(Stephens, et al., 2010)	Algal oil (base case)	510€/ton		High value product[4]	HVP 450€/kg
	Algal oil (projected case)	510 €/ton		Fishmeal substitutes	300€/ton

(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

1. Assume protein by-product are priced based on 2008 average market price for soybean meal.
2. Assume system coupled with anaerobic digestion to produce methane for power generation, Levelised cost of energy is evaluated with discount rate of 5%
3. Assume algal productivity is 60g/m2/day and algal biomass is 60% lipid, system operates 340 days/year, algal cake is sold as animal feed as price is 300$/ton dry basis, carbon credit is 100$/ton;
4. Assume co-product is high value product, such as β-carotene, a sensitivity analysis had been made to evaluate the impact of high value product to cost of algal biomass production
5. All the cost has been normalized into euro, the exchange rate is based on the 2010 average exchange rates from European central bank.

2.10 Conclusions on the economic assessment studies in the literature

Cost assessments in the existing literature[1] are essentially hypothetical in nature. Issues of concern include:

- The limited sources of data. For example, some of the data and assumptions used, are now over two decades old and consequently may not reflect the current state of microalgae culture.
- The use of over-optimistic estimates for algal productivity, CO_2 capture efficiency and system availability. Such estimates often reflect future aspirations rather than currently achievable results.
- The production of co-products, or provision of co-services, greatly affects the economic viability.

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[1] A recent study not included in this analysis is one by Norsker et.al (2011): *Microalgal production — A close look at the economics*. This study compares the cost of micro-algae production in open ponds, flat plate and tubular PBRs. The study concludes that PBRs may ultimately become more attractive than raceway ponds. It should be noted, however, that like the studies reviewed here it is a hypothetical assessment. PBRs come out favourably because the authors choose very optimistic values for the photosynthetic efficiency of PBRs (Tubular 3%, flat panel 5%). The CO_2 cost assumes 100% capture efficiency (1.8 kg CO2/kg biomass) which is unrealistic. The labour and operating costs of the PBR system also appears low.

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3. Economical Assessment of Algae biomass production

This chapter introduces basic concepts for economic assessment, and describes methodologies for conducting techno-economic evaluation. A simple cost model is then used to compare four scenarios for the production of algal biomass in PBRs and raceway ponds. The modeling approach is adapted from a model developed by the University of Almeria (Spain).

3.1 Overview of cost modeling methodologies

A very wide range of production costs of algae derived fuels can be found in the literature. In part this reflects different assumptions for yields, capacities, costs and the state of technology development. But differences also arise from alternate approaches to economic valuation. In particular, there is no single agreed way to calculate the cost for algae biofuel production, select an appropriate discount rate or decide the life of capital equipment. Selecting a modeling methodology is as much a case of deciding what information you wish to exclude from your analysis as it is a case of reviewing what approaches are possible.

At an early stage of development it may be appropriate to use a simple cost analysis to compare alternative systems and guide the engineering development. As the system gets closer to commercial reality, however, more robust financial modeling is necessary.

Most of the existing economic assessments of algae biofuels followed the Process Flow Diagrams methodology (PFD). Process Flow Diagrams (PFD) are used by chemical engineers to show the sequence of equipment and unit operations in a process. A typical flow diagram describes the process as a series of material and energy balance equations which may be determined from experimental or library data.

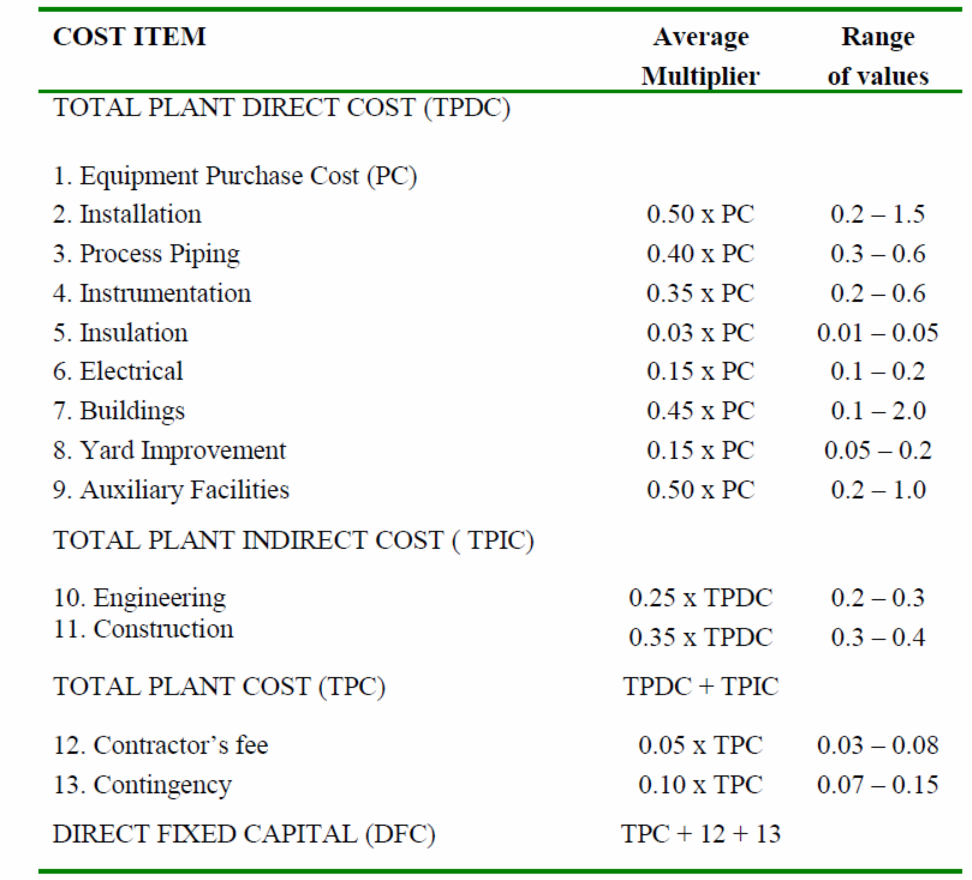
Constructing a process model involves at least three steps:

1. Flowsheet definition: the flowsheet defines the process configuration. It shows all streams entering and exiting the system as well as all unit operations and their interconnecting streams.
2. Chemical component specification: the user must specify all chemical components in the system from reactants to intermediates and products.
3. Operating conditions specification: temperature, pressure, etc. must be specified for each unit operation (Wingren, 2005)

3.2 A simple engineering cost model

In a simple cost model, having determined the basic flowchart, and identified the major equipment and its size, its cost can be determined by using costing equations widely found in the literature. Once the major equipment cost is known, the total fixed capital can be evaluated by using multiplying factors, which give the approximate cost for other equipments and activities, for example installation, pipework, etc. (see Table 3.1) (R.G. and P.W., 2003). The total production cost may then be calculated as the sum of depreciation and direct production costs.

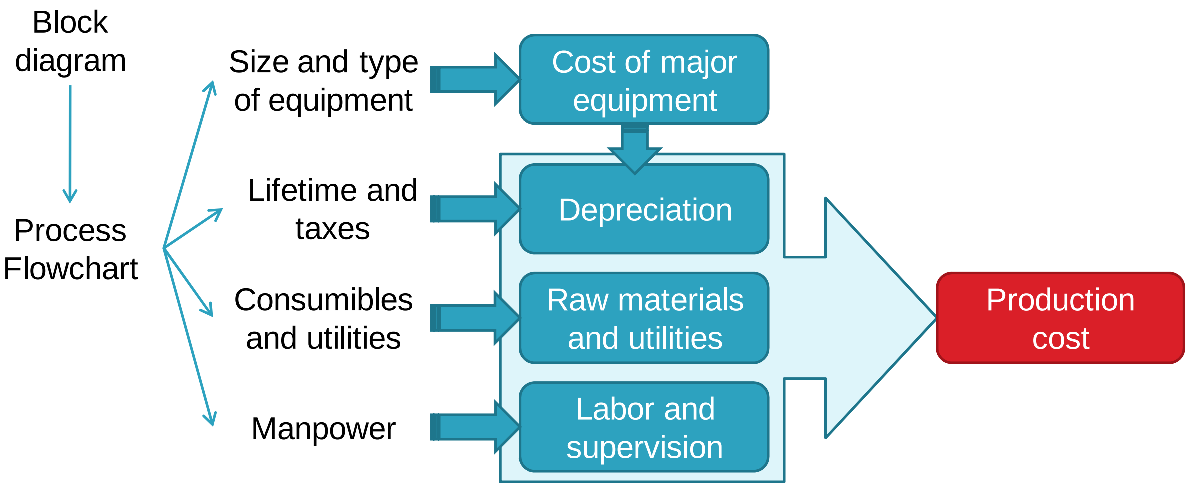
Table 3.1: Illustrative multipliers for fixed capital cost estimation



COST ITEM	Average Multiplier	Range of values
TOTAL PLANT DIRECT COST (TPDC)		
1. Equipment Purchase Cost (PC)		
2. Installation	0.50 x PC	0.2 – 1.5
3. Process Piping	0.40 x PC	0.3 – 0.6
4. Instrumentation	0.35 x PC	0.2 – 0.6
5. Insulation	0.03 x PC	0.01 – 0.05
6. Electrical	0.15 x PC	0.1 – 0.2
7. Buildings	0.45 x PC	0.1 – 2.0
8. Yard Improvement	0.15 x PC	0.05 – 0.2
9. Auxiliary Facilities	0.50 x PC	0.2 – 1.0
TOTAL PLANT INDIRECT COST (TPIC)		
10. Engineering	0.25 x TPDC	0.2 – 0.3
11. Construction	0.35 x TPDC	0.3 – 0.4
TOTAL PLANT COST (TPC)	TPDC + TPIC	
12. Contractor's fee	0.05 x TPC	0.03 – 0.08
13. Contingency	0.10 x TPC	0.07 – 0.15
DIRECT FIXED CAPITAL (DFC)	TPC + 12 + 13	

The cost modeling scheme used in this report is shown in **Figure 3.1**. Direct production cost includes raw materials and utilities, in addition to labor and other cost. The life of the depreciated assets for the facility is assumed to be 10 years. The rate raw materials consumption can be calculated from mass balances to the system, whereas utilities can be quantified from the power and water use of process. Labor costs covers manpower for the system operation, but also includes costs of supervision and management, in addition to maintenance, taxes, contingency**.**

Figure 3.1 cost analysis methodology.



3.3 Key cost parameters for the production of microalgae biomass

Before performing the economic analysis, it is useful to review the main factors for the production of microalgae biomass. These are:

1. *Strain and its specific growth parameters:*

The strain to be produced must be defined. Different strains have different requirements respect to light and temperature but also with respect to nutrients availability, pH of the culture, and tolerance to hydrodynamic stress or excessive irradiance. If a complete growth model of the micro-algal strains selected is available it can be included into the calculations to determine the variation of biomass productivity as a function of environmental factors. Alternatively empirical data of biomass productivity according to the culture conditions are necessary.

2. *Location and overall weather conditions:*

The location of the facility is a major factor because it determines the solar radiation availability in addition to air temperature. Solar radiation is the energy source for the process a linear relationship between light availability and biomass productivity being expected. The slope of this variation is a function of the management of the culture (adequate culture conditions) but also of the design of the reactor and its operation (dilution rate, etc.).

3. Design of the reactor:

Different designs of photo-bioreactors have been proposed, most of them being classified in three major groups: open, flat and tubular. However, including in each group different configurations can be selected. The design of the reactor will determine two major parameters necessary for the economic modelling: (i) the specific power consumption and (ii) the surface to volume ratio (S/V) of the reactor. Specific power consumption is the energy consumption necessary per cubic meter of culture during operation of the system. This includes not only the power consumed for mixing or liquid circulation, but also the power required to supply CO_2 or remove oxygen. It also includes the power required to impulse the culture in and out of the reactor, for temperature control and whatever other mechanical system. The S/V ratio defines the surface of the reactor exposed to light per culture volume. This parameter is determined by the geometry of the reactor and its configuration.

4. Harvesting procedure:

According to the selected strain and the culture conditions, the size of the cells and their state can vary greatly. The size and state of the cells directly influences the process required to harvest the biomass and concentrate it. Large cells or filamentous strains are easily harvested by flocculation-decantation whereas small cells require the use of centrifugation units. To avoid the use of expensive centrifugation steps flocculation has also been proposed for small cells, but the effectiveness of this approach must be verified at large scale.

5. Water and nutrients supply:

The production of microalgae involves the management of large volumes of water, thus the cost of water and availability must be known. In addition, water must be supplemented with mineral nutrients, mainly fertilizers; the cost of which must also be included. To avoid the use of freshwater, it has been suggested that “low quality water“such as seawater or brakishwater might be used. Re-circulating water can reduce the water consumption (and reduce nutrient costs) but recirculation imposes other cost related to the water treatment which required before the water can be re-used. There is also a greater risk of infection and inhibition: bBacteria, fungi, viruses are found in greater concentrations in recycled waters, along with non-living inhibitors such as organic and inorganic chemicals and remaining metabolites from destroyed algae cells. In any case a fraction of the overall water must be reposed to purge contaminants and maintain the salinity of the medium.

6. Carbon source:

Approximately half of the weight of produced algal biomass is carbon, thus large amounts of carbon dioxide are required to produce microalgal biomass at large scale. Although stoichiometrically only 2 kg of carbon dioxide are necessary to produce 1kg of microalgal biomass, owing to the low efficiency in carbon absorption, this value increases up to 3-4 kg (or more) of carbon dioxide per 1 kg of dry biomass produced. The cost of carbon dioxide is thus highly relevant to the biomass production cost, the use of flue gases may provide a low cost source of CO_2, but using this source will necessitate the use of cleaning and conditioning units to prevent micro-algae from being poisoned. The cost of these units and their power consumption must be also included into the economical analysis.

3.4 System boundaries

In the analysis presented here, raceway ponds and photobioreactors (PBR) are compared. The process steps are limited to cultivation and harvesting in both cases.

For the PBR system (**Figure 3.2**), the process includes automatic preparation of culture medium by adding fertilizers to water, and then sterilization by filtration. The culture medium is then pumped around tubular PBRs. When the algae cells have accumulated the lipid (Tri-acylglycerides) to a sufficient level, the algae is settled using flocculants. This process yields a sludge that is centrifuged in continuous mode decanter to obtain a 15% dry matter paste.

In the raceway pond (**Figure 3.3**), culture preparation is simpler, the medium is prepared by adding fertilizers to the water directly and filtration is not required.

Figure 3.2: Flowchart of the production process using tubular PBRs

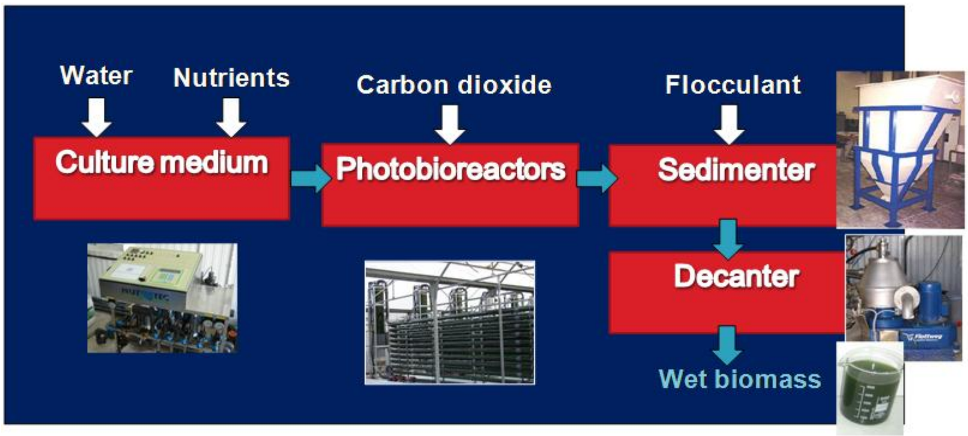
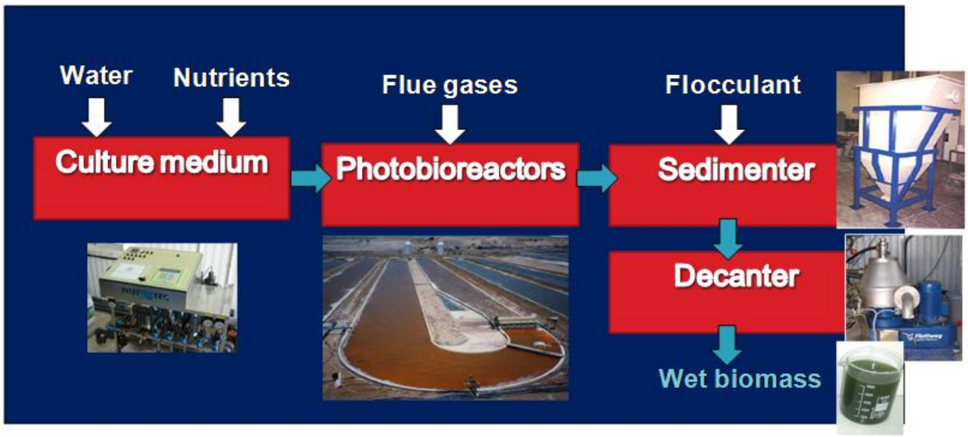


Figure 3.3: Flowchart of the production process using Open raceway pond



3.5 Description of the scenarios

Four scenarios for algae biofuel production are compared. The first two scenarios are a 'base case', and aim to illustrate what can be achieved by integrating current technology. Scenarios 3 and scenario 4 are a 'projected case' which is aims to illustrate what might be possible if technical advances occur.

The *projected case* differs from the *base case* in the following assumptions:

- Operating days per year (availability) are increased from 10 months to 12months.
- The use of alternative sources of CO_2 (e.g. flue gases, wastes) and nutrients (wastewater) is assumed.
- It is assumed that high biomass productivity by selected algae strains is achievable.

An overview of the four scenarios is provided in Table 3.2 and Table 3.3

Table 3.2: The four scenarios for raceway ponds

Scenario	**Pond Area (ha)**	**Biomass productivity (g/m^2/day)**	**Operating days (day) (availability)**	**Power consumption (W/m^2)**	**Water evaporation (L/m^2/day)**	**Raw Materials costs[1]**
Scenario1 (Base case)	400	10	300	1	10	Cost of water, CO2, and nutrients has been included
Scenario2 (Base case)	400	10	360	1	10	
Scenario3 (projected case)	400	20	300	1	10	Cost of water, CO2 , and nutrients are not included
Scenario4 (projected case)	400	20	360	1	10	

1. Raw materials include water, nutrients and CO_2.

Table 3.3: The four scenarios for photobioreactors (PBR)

Scenario	**Pond Area (ha)**	**Biomass productivity (g/m^2/day)**	**Operating days (day) (availability)**	**Power consumption (W/m^2)**	**Water evaporation (L/m^2/day)**	**Raw Materials costs[1]**
Scenario1 (Base case)	10	20	300	500	0.5	Cost of water, CO2, and nutrients has been included
Scenario2 (Base case)	10	20	360	500	0.5	
Scenario3 (projected case)	10	40	300	50	0.5	Cost of water, CO2 , and nutrients are not included
Scenario4 (projected case)	10	40	360	50	0.5	

1. Raw materials include water, nutrients and CO_2.

All the scenarios assumed 400ha land area for open raceway system, and 10ha for closed photobioreactors (PBR). The utilities assumptions depend on the season and system, but only include the pumping cost for water.

Two biomass productivity assumptions are considered. For the base case, data is based on the judgment and experience by the AquaFUELs project partners; it is assumed that we could get 10g/m^2/day biomass in the open raceway system and 20g/m^2/day in the photobioreactor. For the projected case, data is based on the extrapolation of the experimental data and technical advances which it is assumed can be achieved in the future; it is assumed that we could get 20g/m^2/day in the open system and 40g/m^2/day in the photobioreactor.

For all the cases, after dewatering process, the liquid medium is recycled, at least in part, back to the algae growth units. In the projected case, municipal wastewater is assumed to be the source of all water and nutrient input and most of the carbon input.

A critical difference between the scenarios is the source of CO_2. In the base case it is assumed that CO_2 is purchased from the market. In the projected case it is assumed that sources of carbon, such as flue gas from nearby power plant, are available thus the CO_2 is assumed to be free. (It is worth noting, however, that in reality additional costs may be incurred for pumping and clean-up)

Existing literature mentions that, high value co-products may underpin the profitability of large plants. However, there is likelihood that production of high value products at a single large facility would saturate a relative small market so no particular product is assumed in this model.

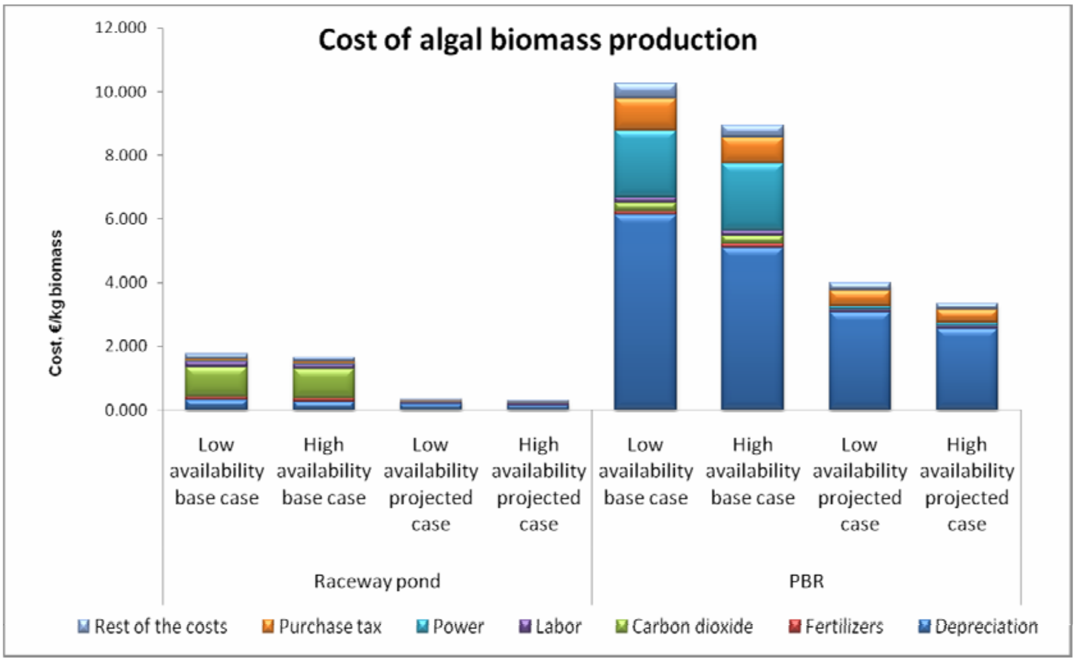
Several studies have also emphasized that a credit for wastewater treatment may be able to produce cost-competitive biofuels. However, a certain scale, the needs for locations in sunny climates with access to sufficient flat land and CO_2. So integration with wastewater treatment service is not included in this study (we only assumed we could get free water and nutrients from wastewater facility in the future).

A complete breakdown of the other assumptions required to develop the modeling and associated cost estimates are described in the **Annex 2 & 3**.

3.6 Results:

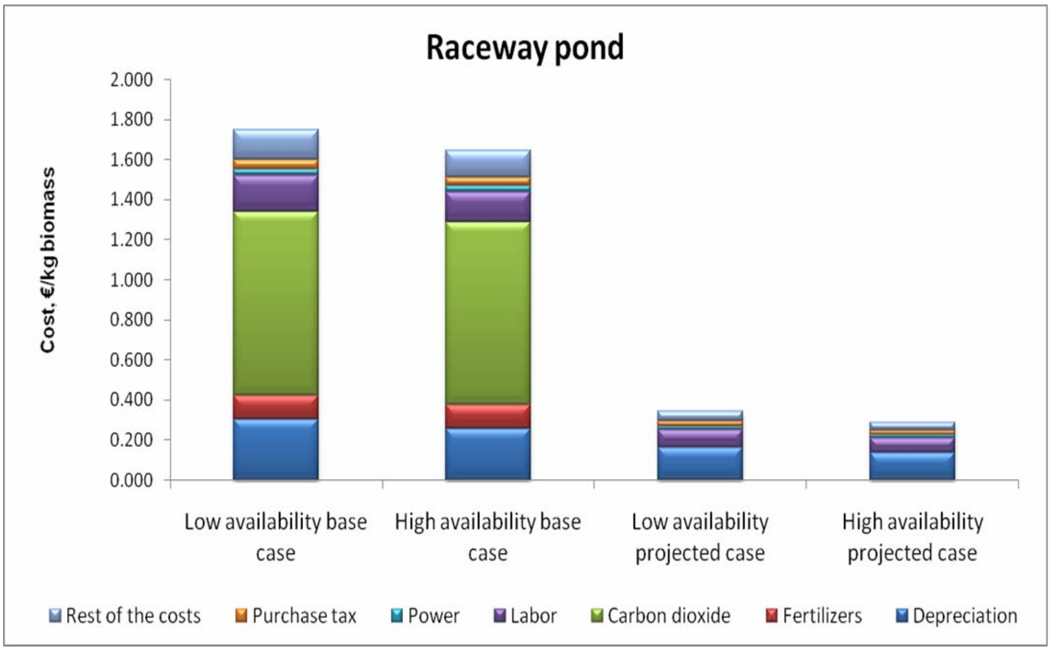
A comparison of the cost of producing algal biomass in raceway ponds and PBR systems for each of the four scenarios is shown in **Figure 3.4.** Overall it can be seen that producing biomass in a PBR (4-10€/kg) is roughly 5-10 times more expensive than in raceway ponds (0.4-1.8€/kg). It can also be seen that there is little difference between the low and high availability cases (~5%), whereas moving from the base case to the projected case results in a ~50% decrease in costs. For comparison, the market price for delivered woody biomass pellets in the UK is ~ 0.2-0.4€/kg (E4tech, 2010). Although, it should be noted that the composition and potential uses of algal biomass are far more interesting.

Figure 3.4: Breakdown of cost estimates for both Raceway Pond and PBR



The production cost of algal biomass from raceway pond systems is shown in **Figure 3.5**, expanded to better show the costs from different categories. Both the base case scenarios consume a great deal of CO_2 (because the open pond system has poor CO_2 fixation performance), and this dominates the production cost (~1.8€/kg). The projected case gives a much reduced cost (~0.25€/kg). This is due to both the higher productivity assumption and the assumption that the CO_2 comes from an adjacent power plant and is free of charge. Another source of variation between the scenarios is the fertilizer costs: in the projected scenario we assume the cultivation system is coupled with a wastewater treatment facility, and that nutrients are also effectively free of charge. Only in this optimistic scenario can the production cost approach the level required to service the biofuels market.

Figure 3.5: Cost of algal biomass production in raceway pond systems



The production cost of algal biomass produced in the PBR systems is shown in **Figure 3.6.** In the base case the cost is ~9-10€/kg and in the projected case the cost is ~3.8€/kg. All the scenarios are dominated by system capital cost. The CO_2 cost in the PBR system is proportionately less important than in the raceway pond, this is partly because the PBR system has better CO_2 fixation performance, and partly because the amount of electricity consumed in the PBR system is greater. In the projected case, where raw materials are effectively free and the power consumption has been reduced by 90%, the cost of biomass production is greatly reduced (from ~9€/kg to ~3.8€/kg) but is still greater than the cost of production in raceway ponds. Again, only with a dramatic reduction in the system capital cost can the production cost approach the level required to service the biofuels market.

Figure 3.6: Cost of algal biomass production in a tubular photobioreactor system

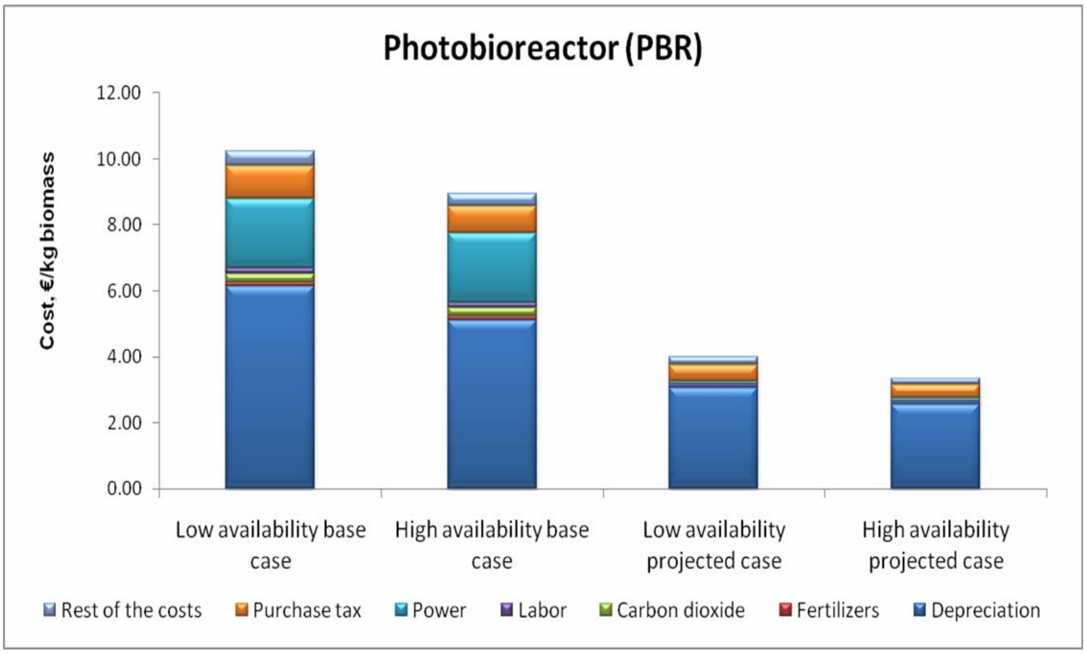
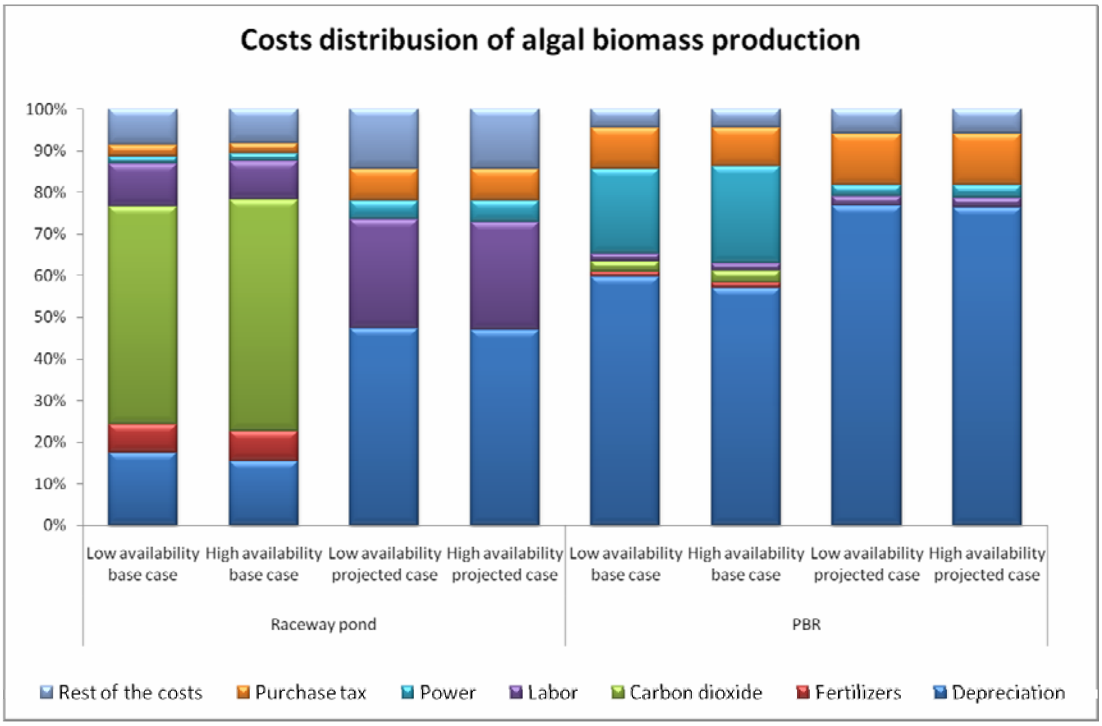


Figure 3.7 shows the percentage contribution of the different cost elements to the overall biomass production cost. This figure shows clearly that production in PBRs is dominated by the capital cost, whereas production in a raceway pond is dominated by raw materials and operational costs.

Figure 3.7: Distribution of the cost of algal biomass production



3.7 Conclusions

The results shown here are for a partially complete system estimated using a simple costing model. This model is appropriate to identifying the cost elements of the process that pose the greatest challenge to engineering development. It is likely, however, to underestimate the true cost of algae production. This is because a real project would incur other significant costs such as the cost of finance and the cost of land which have been excluded from this analysis. The two future scenarios also postulate dramatic improvements in technical performance that may, or may not, be achieved.

With these important caveats in mind, we consider that this analysis supports the following conclusions.

- Raceway pond systems demonstrate a lower cost of algal biomass production than photo-bioreactor systems.
- Most of the costs in raceway system production are associated with operation (labor, utilities and raw materials). The costs of PBRs in contrast are dominated by the capital cost of the PBRs.
- Dramatic improvements in both productivity and energy efficiency would be required to greatly reduce the cost of biomass production.
- Significant (>50%) cost reductions may be achieved if CO_2, nutrients and water can be obtained at zero cost. This is a very demanding requirement, however, and it could dramatically restrict the number of locations available.

- Compared with other sources of biomass used for energy, algal biomass appears expensive.

4. Synopsis of the AquaFUELs roundtable on the state of the art and future perspectives for algae biofuels

4.1 Background

The AquaFUELs project hosted a roundtable meeting on 21st-22nd October 2010. This meeting gathered experts in algae production from across Europe with the aim of fostering critical thinking on the state of the art and future perspectives for algae biofuels. During the meeting the economic prospects of algae biofuels were discussed and debated. This chapter presents a brief synopsis of the elements of the discussion that directly concerned economic assessment. A full transcript of the meeting can be found on the Aquafuels project website at the following location:
http://www.aquafuels.eu/attachments/078_D_2.2_Proceedings.pdf

4.2 Synopsis

Stakeholders identified a number of problems with existing assessments of micro-algae economics. In particular the use of optimistic projections of future performance that were not realistic.

4.2.1 Productivity

Prof. Boussiba (Bengurion University) gave the example of productivity claims of 60,000 to 240,000 litres of algae oil per hectare per year, which were in excess of twice the theoretical efficiency of photosynthesis. He considered that limiting factors (solar energy, scattering and reflecting, cell/surface properties, absorption spectrum, photosynthetic efficiency, light saturation, maintenance, photo-inhibition and temperature) would only allow ~24 g/m2/day productivity, i.e. 80 tons per hectare per year.

Dr. Leu (Bengurion University) commented that no increase in photosynthetic efficiency had been achieved by genetic modification so far, only resistance to insects or biocides. He estimated that productivity would not go up, but that robustness could be increased. He doubted that photosynthetic efficiency could ever be increased.

Dr. Vanhoutte (Beko Consulting) noted that algae were generally thought of as primitive organisms, which they were not. The ambition of synthetic genomics to “build an algae” overlooks the complexity of that endeavour.

4.2.2 Cost of inputs

The cost of inputs was raised as an issue by Prof. Tredici (University of Florence). He noted that the cost of labour was a major issue in the calculation of costs, and commented that a cost of 0.5€/kg would be achievable provided that the CO_2 and the nutrients were free and that the algae production facility were close to the sea and to the CO_2 source [to reduce pumping costs].

4.2.3 Co-product markets

The complexity of servicing co-product markets was also discussed. For example, growing algae bio-protein on wastewater and selling this for animal feed might be technically possible, but would be prohibited by EU animal feed regulations that effectively bans the use of wastewater and all derived products in animal feed.

Dr. Leu (Ben-Gurion University) noted that there could be a market for by-products as long as production remained limited, but that producing massive quantities of algae would eventually lead to kill these markets.

4.2.4 Potential to compete with fossil fuels

Prof. Boussiba (Ben-Gurion University) asked if algae biofuels should really try to compete with oil, as reaching the price of oil seemed unrealistic. He argued that any other application would be more interesting: the biofuels market was the least attractive option for the algae sector. Whereas feed, chemicals, special food and other applications would all prove more interesting. He further noted that biofuels feedstock were currently available at 0.5$/kg while current algae production was in all cases above 5$/kg.

Dr. Garcia-Reina added that researchers should interpret the research carried out until now on algae biofuels as an invitation not to underestimate the technical hurdles to algae production. He cautioned against extrapolating the potential of algae biofuels from the work done to date.

4.3 Conclusions

The overall conclusion of the roundtable meeting was that cost of algae biofuels was generally estimated to be close to 4-5€/kg, while the target price was estimated at 0.4-0.5€/kg. A decrease in price by ten to fifty times was therefore needed to reach commercial viability.

It was also apparent that experts in algae production are cautious about its future prospects for use as a biofuel feedstock. There was a consensus that biofuels could not be the only end market, co-product and co-service valorisation would also be necessary.

Despite this caution, numerous options to decrease the cost of algae production are anticipated, for example, by scaling up production and overcoming the bottleneck of harvesting, extraction and dewatering. Increased productivity through improved biology and biotechnology could also balance the high costs of algae production. Increasing the efficiency of photosynthesis, however, is considered unlikely.

5. **Conclusions**

This report examines the available literature on the cost of micro-algae biomass production, and develops a simple cost model which is used to compare scenarios for micro-algae production in raceway ponds and photo-bioreactors (PBRs).

From our review of the literature we conclude that:

- Cost assessments in the existing literature are hypothetical in nature. There are limited sources of primary data: some sources and assumptions are over two decades old and may not reflect the current state of microalgae culture.
- Estimates and assumptions, particularly those for *algal productivity*, *CO_2 capture efficiency* and *system availability* often reflect future aspirations rather than currently achievable results.
- The production of co-products, or provision of co-services, greatly affects estimates of economic viability.

From our comparison of production scenarios we conclude that:

- Raceway pond systems demonstrate a lower cost of algal biomass production than photo-bioreactor systems.
- Dramatic improvements in both productivity and energy efficiency would be required to reduce the cost of production.
- Significant (>50%) cost reductions may be achieved if CO_2 and nutrients and water could be obtained at zero cost. This is a very demanding requirement, and could dramatically restrict the number of suitable locations for development.
- Compared with other sources of biomass used to for energy generation, algal biomass appears expensive.

From the discussion of the economics of algae production, held at the AquaFUELs roundtable in 2010, we conclude that:

- Experts in algae production are cautious about its future prospects for use as a biofuel feedstock. There was a consensus that biofuels could not be the only end market, co-product and co-service valorisation would be essential.
- Many opportunities to reduce costs exist though improved engineering and biotechnology,

Cost assessments of micro-algae production are at an early stage of development. They are appropriate to guide engineering development, and test the sensitivity of design assumptions, but they are insufficient to guide policy or investment decisions in anything but the broadest of terms.

Improving on the existing cost estimates will require empirical data on the performance of systems designed specifically to produce biofuels. Ideally this date would come from systems operated for an extended period of time at large scale.

6. **References**

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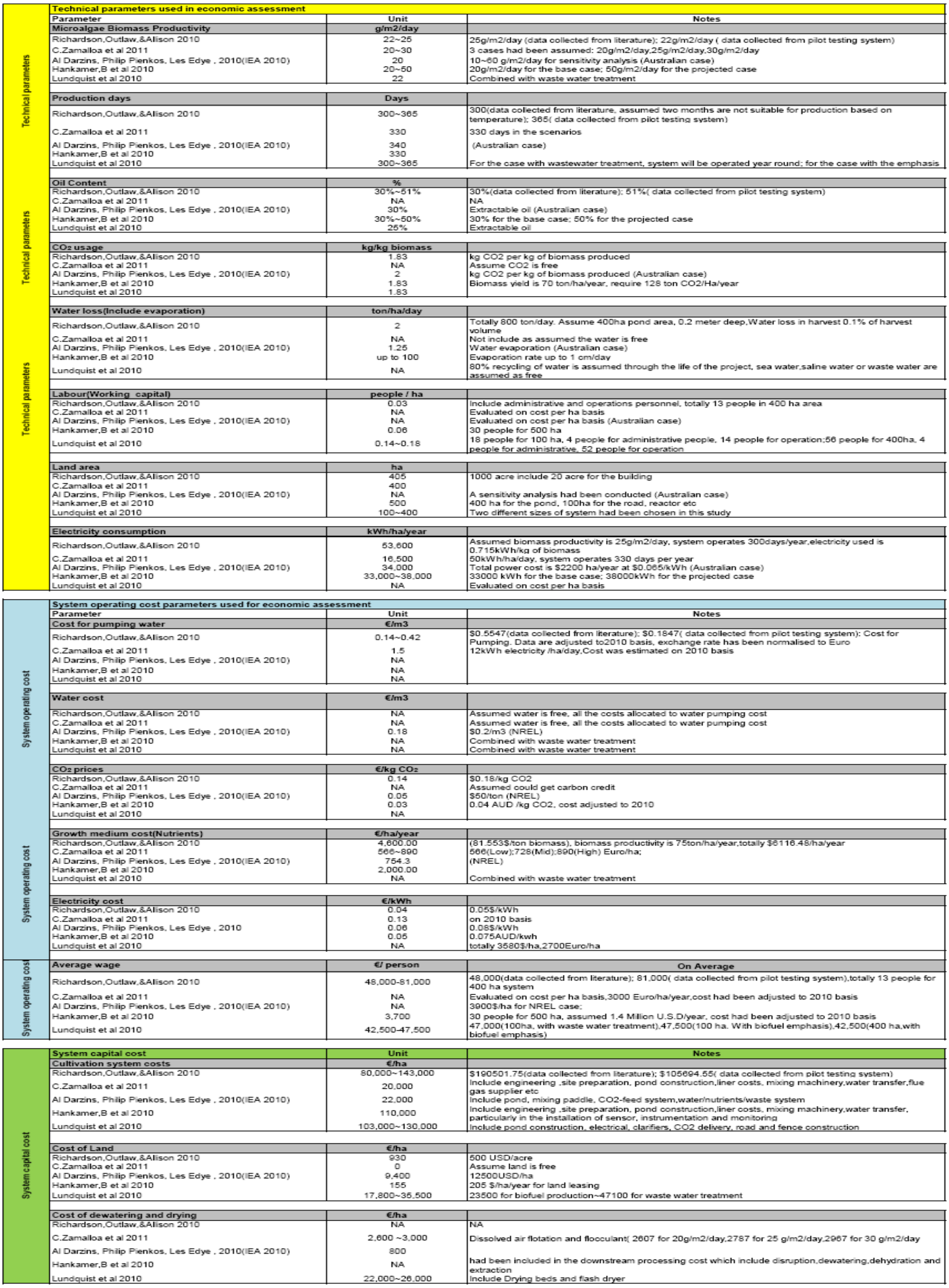
7. Annex 1: Expert stakeholders participating in this report

Name	Institution
Mathieu Streefland	Wageningen University, Netherlands
Rene Wiffles	Wageningen University, Netherlands
Emilio Molina Grima	University of Almeria, Spain
Francisco G. Acien Fernandez	University of Almeria, Spain
MarioTredici	University of Florence, Italy
Niccolo Bassi	University of Florence, Italy
Sammy Boussiba	Ben Gurion University
Guillermo Garcia Reina	Centro de Biotecnologia Marina, University of Las Palmas de Gran Canaria
Laurenz Thomsen	Jacobs University Bremen

8. Annex 2: Assumptions applied in the existing Economic Assessment



	Technical parameters used in economic assessment		
	Parameter	**Unit**	**Notes**
Technical parameters	**Microalgae Biomass Productivity**	**g/m2/day**	
	Richardson,Outlaw,&Alison 2010	22~25	25g/m2/day (data collected from literature); 22g/m2/day (data collected from pilot testing system)
	C.Zamalloa et al 2011	20~30	3 cases had been assumed: 20g/m2/day,25g/m2/day,30g/m2/day
	Al Darzins, Philip Pienkos, Les Edye , 2010(IEA 2010)	20	10~60 g/m2/day for sensitivity analysis (Australian case)
	Hankamer,B et al 2010	20~50	20g/m2/day for the base case; 50g/m2/day for the projected case
	Lundquist et al 2010	22	Combined with waste water treatment
	Production days	**Days**	
	Richardson,Outlaw,&Alison 2010	300~365	300(data collected from literature, assumed two months are not suitable for production based on temperature); 365(data collected from pilot testing system)
	C.Zamalloa et al 2011	330	330 days in the scenarios
	Al Darzins, Philip Pienkos, Les Edye , 2010(IEA 2010)	340	(Australian case)
	Hankamer,B et al 2010	330	
	Lundquist et al 2010	300~365	For the case with wastewater treatment, system will be operated year round; for the case with the emphasis
Technical parameters	**Oil Content**	**%**	
	Richardson,Outlaw,&Alison 2010	30%~51%	30%(data collected from literature); 51%(data collected from pilot testing system)
	C.Zamalloa et al 2011	NA	NA
	Al Darzins, Philip Pienkos, Les Edye , 2010(IEA 2010)	30%	Extractable oil (Australian case)
	Hankamer,B et al 2010	30%~50%	30% for the base case; 50% for the projected case
	Lundquist et al 2010	25%	Extractable oil
	CO_2 usage	**kg/kg biomass**	
	Richardson,Outlaw,&Alison 2010	1.83	kg CO2 per kg of biomass produced
	C.Zamalloa et al 2011	NA	Assume CO2 is free
	Al Darzins, Philip Pienkos, Les Edye , 2010(IEA 2010)	2	kg CO2 per kg of biomass produced (Australian case)
	Hankamer,B et al 2010	1.83	Biomass yield is 70 ton/ha/year, require 128 ton CO2/Ha/year
	Lundquist et al 2010	1.83	
Technical parameters	**Water loss(Include evaporation)**	**ton/ha/day**	
	Richardson,Outlaw,&Alison 2010	2	Totally 800 ton/day. Assume 400ha pond area, 0.2 meter deep,Water loss in harvest 0.1% of harvest volume
	C.Zamalloa et al 2011	NA	Not include as assumed the water is free
	Al Darzins, Philip Pienkos, Les Edye , 2010(IEA 2010)	1.25	Water evaporation (Australian case)
	Hankamer,B et al 2010	up to 100	Evaporation rate up to 1 cm/day
	Lundquist et al 2010	NA	80% recycling of water is assumed through the life of the project, sea water,saline water or waste water are assumed as free
	Labour(Working capital)	**people / ha**	
	Richardson,Outlaw,&Alison 2010	0.03	Include administrative and operations personnel, totally 13 people in 400 ha area
	C.Zamalloa et al 2011	NA	Evaluated on cost per ha basis
	Al Darzins, Philip Pienkos, Les Edye , 2010(IEA 2010)	NA	Evaluated on cost per ha basis (Australian case)
	Hankamer,B et al 2010	0.06	30 people for 500 ha
	Lundquist et al 2010	0.14~0.18	18 people for 100 ha, 4 people for administrative people, 14 people for operation;56 people for 400ha, 4 people for administrative, 52 people for operation
	Land area	**ha**	
	Richardson,Outlaw,&Alison 2010	405	1000 acre include 20 acre for the building
	C.Zamalloa et al 2011	400	
	Al Darzins, Philip Pienkos, Les Edye , 2010(IEA 2010)	NA	A sensitivity analysis had been conducted (Australian case)
	Hankamer,B et al 2010	500	400 ha for the pond, 100ha for the road, reactor etc
	Lundquist et al 2010	100~400	Two different sizes of system had been chosen in this study
	Electricity consumption	**kWh/ha/year**	
	Richardson,Outlaw,&Alison 2010	53,600	Assumed biomass productivity is 25g/m2/day, system operates 300days/year,electricity used is 0.715kWh/kg of biomass
	C.Zamalloa et al 2011	16,500	50kWh/ha/day, system operates 330 days per year
	Al Darzins, Philip Pienkos, Les Edye , 2010(IEA 2010)	34,000	Total power cost is $2200 ha/year at $0.065/kWh (Australian case)
	Hankamer,B et al 2010	33,000~38,000	33000 kWh for the base case; 38000kWh for the projected case
	Lundquist et al 2010	NA	Evaluated on cost per ha basis

	System operating cost parameters used for economic assessment		
	Parameter	**Unit**	**Notes**
System operating cost	**Cost for pumping water**	**€/m3**	
	Richardson,Outlaw,&Alison 2010	0.14~0.42	$0.5547(data collected from literature); $0.1847(data collected from pilot testing system): Cost for Pumping. Data are adjusted to2010 basis, exchange rate has been normalised to Euro
	C.Zamalloa et al 2011	1.5	12kWh electricity /ha/day,Cost was estimated on 2010 basis
	Al Darzins, Philip Pienkos, Les Edye , 2010(IEA 2010)	NA	
	Hankamer,B et al 2010	NA	
	Lundquist et al 2010	NA	
	Water cost	**€/m3**	
	Richardson,Outlaw,&Alison 2010	NA	Assumed water is free, all the costs allocated to water pumping cost
	C.Zamalloa et al 2011	NA	Assumed water is free, all the costs allocated to water pumping cost
	Al Darzins, Philip Pienkos, Les Edye , 2010(IEA 2010)	0.18	$0.2/m3 (NREL)
	Hankamer,B et al 2010	NA	Combined with waste water treatment
	Lundquist et al 2010	NA	Combined with waste water treatment
	CO_2 prices	**€/kg CO_2**	
	Richardson,Outlaw,&Alison 2010	0.14	$0.18/kg CO2
	C.Zamalloa et al 2011	NA	Assumed could get carbon credit
	Al Darzins, Philip Pienkos, Les Edye , 2010(IEA 2010)	0.05	$50/ton (NREL)
	Hankamer,B et al 2010	0.03	0.04 AUD /kg CO2, cost adjusted to 2010
	Lundquist et al 2010	NA	
System operating cost	**Growth medium cost(Nutrients)**	**€/ha/year**	
	Richardson,Outlaw,&Alison 2010	4,600.00	(81.553$/ton biomass), biomass productivity is 75ton/ha/year,totally $6116.48/ha/year
	C.Zamalloa et al 2011	566~890	566(Low);728(Mid);890(High) Euro/ha;
	Al Darzins, Philip Pienkos, Les Edye , 2010(IEA 2010)	754.3	(NREL)
	Hankamer,B et al 2010	2,000.00	
	Lundquist et al 2010	NA	Combined with waste water treatment
	Electricity cost	**€/kWh**	
	Richardson,Outlaw,&Alison 2010	0.04	0.05$/kWh
	C.Zamalloa et al 2011	0.13	on 2010 basis
	Al Darzins, Philip Pienkos, Les Edye , 2010	0.06	0.08$/kWh
	Hankamer,B et al 2010	0.05	0.075AUD/kwh
	Lundquist et al 2010	NA	totally 3580$/ha,2700Euro/ha
System operating cost	**Average wage**	**€/ person**	**On Average**
	Richardson,Outlaw,&Alison 2010	48,000-81,000	48,000(data collected from literature); 81,000(data collected from pilot testing system),totally 13 people for 400 ha system
	C.Zamalloa et al 2011	NA	Evaluated on cost per ha basis,3000 Euro/ha/year,cost had been adjusted to 2010 basis
	Al Darzins, Philip Pienkos, Les Edye , 2010(IEA 2010)	NA	3900$/ha for NREL case;
	Hankamer,B et al 2010	3,700	30 people for 500 ha, assumed 1.4 Million U.S.D/year, cost had been adjusted to 2010 basis
	Lundquist et al 2010	42,500-47,500	47,000(100ha, with waste water treatment),47,500(100 ha. With biofuel emphasis),42,500(400 ha,with biofuel emphasis)

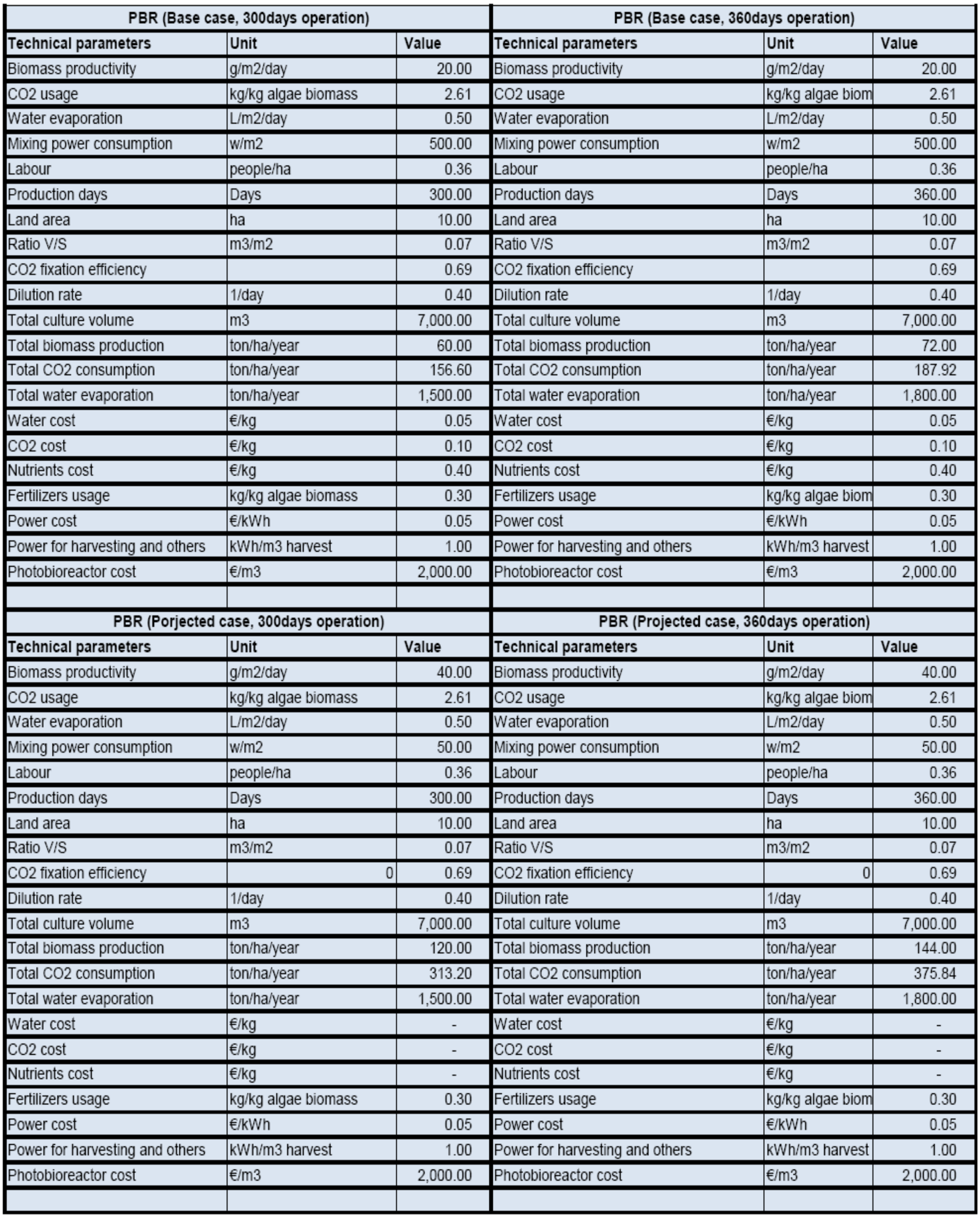
	System capital cost	Unit	Notes
System capital cost	**Cultivation system costs**	**€/ha**	
	Richardson,Outlaw,&Alison 2010	80,000~143,000	$190501.75(data collected from literature); $105694.55(data collected from pilot testing system)
	C.Zamalloa et al 2011	20,000	Include engineering ,site preparation, pond construction,liner costs, mixing machinery,water transfer,flue gas supplier etc
	Al Darzins, Philip Pienkos, Les Edye , 2010(IEA 2010)	22,000	Include pond, mixing paddle, CO2-feed system,water/nutrients/waste system
	Hankamer,B et al 2010	110,000	Include engineering ,site preparation, pond construction,liner costs, mixing machinery,water transfer, particularly in the installation of sensor, instrumentation and monitoring
	Lundquist et al 2010	103,000~130,000	Include pond construction, electrical, clarifiers, CO2 delivery, road and fence construction
	Cost of Land	**€/ha**	
	Richardson,Outlaw,&Alison 2010	930	500 USD/acre
	C.Zamalloa et al 2011	0	Assume land is free
	Al Darzins, Philip Pienkos, Les Edye , 2010(IEA 2010)	9,400	12500USD/ha
	Hankamer,B et al 2010	155	205 $/ha/year for land leasing
	Lundquist et al 2010	17,800~35,500	23500 for biofuel production~47100 for waste water treatment
	Cost of dewatering and drying	**€/ha**	
	Richardson,Outlaw,&Alison 2010	NA	NA
	C.Zamalloa et al 2011	2,600 ~3,000	Dissolved air flotation and flocculant(2607 for 20g/m2/day,2787 for 25 g/m2/day,2967 for 30 g/m2/day
	Al Darzins, Philip Pienkos, Les Edye , 2010(IEA 2010)	800	
	Hankamer,B et al 2010	NA	had been included in the downstream processing cost which include disruption,dewatering,dehydration and extraction
	Lundquist et al 2010	22,000~26,000	Include Drying beds and flash dryer

9. Annex 3: Technical parameters of Raceway Pond system used in the Economic Model

Raceway Pond (Base case, 300days operation)			Raceway Pond (Base case, 360days operation)		
Technical parameters	**Unit**	**Value**	**Technical parameters**	**Unit**	**Value**
Biomass productivity	g/m2/day	10.00	Biomass productivity	g/m2/day	10.00
CO2 usage	kg/kg algae biomass	9.15	CO2 usage	kg/kg algae biomass	9.15
Water evaporation	L/m2/day	10.00	Water evaporation	L/m2/day	10.00
Mixing power consumption	w/m2	1.00	Mixing power consumption	w/m2	1.00
Labour	people/ha	0.18	Labour	people/ha	0.18
Production days	Days	300.00	Production days	Days	360.00
Land area	ha	400.00	Land area	ha	400.00
Ratio V/S	m3/m2	0.25	Ratio V/S	m3/m2	0.25
CO2 fixation efficiency		0.20	CO2 fixation efficiency		0.20
Dilution rate	1/day	0.02	Dilution rate	1/day	0.02
Total culture volume	m3	1000000.00	Total culture volume	m3	1000000.00
Total biomass production	ton/ha/year	30.00	Total biomass production	ton/ha/year	36.00
Total CO2 consumption	ton/ha/year	274.50	Total CO2 consumption	ton/ha/year	329.40
Total water evaporation	ton/ha/year	30000.00	Total water evaporation	ton/ha/year	36000.00
Water cost	€/kg	0.05	Water cost	€/kg	0.05
CO2 cost	€/kg	0.10	CO2 cost	€/kg	0.10
Nutrients cost	€/kg	0.40	Nutrients cost	€/kg	0.40
Fertilizers usage	kg/kg algae biomass	0.30	Fertilizers usage	kg/kg algae biomass	0.30
Power cost	€/kWh	0.05	Power cost	€/kWh	0.05
Power for harvesting and others	kWh/m3 harvest	1.00	Power for harvesting and others	kWh/m3 harvest	1.00
Photobioreactor cost	€/m3	10.00	Photobioreactor cost	€/m3	10.00

Raceway Pond (Projected case, 300days operation)			Raceway Pond (Projected case, 360days operation)		
Technical parameters	**Unit**	**Value**	**Technical parameters**	**Unit**	**Value**
Biomass productivity	g/m2/day	20.00	Biomass productivity	g/m2/day	20.00
CO2 usage	kg/kg algae biomass	9.15	CO2 usage	kg/kg algae biomass	9.15
Water evaporation	L/m2/day	10.00	Water evaporation	L/m2/day	10.00
Mixing power consumption	w/m2	1.00	Mixing power consumption	w/m2	1.00
Labour	people/ha	0.18	Labour	people/ha	0.18
Production days	Days	300.00	Production days	Days	360.00
Land area	ha	400.00	Land area	ha	400.00
Ratio V/S	m3/m2	0.25	Ratio V/S	m3/m2	0.25
CO2 fixation efficiency	0	0.20	CO2 fixation efficiency	0	0.20
Dilution rate	1/day	0.02	Dilution rate	1/day	0.02
Total culture volume	m3	1000000.00	Total culture volume	m3	1000000.00
Total biomass production	ton/ha/year	60.00	Total biomass production	ton/ha/year	72.00
Total CO2 consumption	ton/ha/year	549.00	Total CO2 consumption	ton/ha/year	658.80
Total water evaporation	ton/ha/year	30000.00	Total water evaporation	ton/ha/year	36000.00
Water cost	€/kg	0.00	Water cost	€/kg	0.00
CO2 cost	€/kg	0.00	CO2 cost	€/kg	0.00
Nutrients cost	€/kg	0.00	Nutrients cost	€/kg	0.00
Fertilizers usage	kg/kg algae biomass	0.30	Fertilizers usage	kg/kg algae biomass	0.30
Power cost	€/kWh	0.05	Power cost	€/kWh	0.05
Power for harvesting and others	kWh/m3 harvest	1.00	Power for harvesting and others	kWh/m3 harvest	1.00
Photobioreactor cost	€/m3	10.00	Photobioreactor cost	€/m3	10.00

10. Annex 4: Technical parameters of Photobioreactor used in the Economic Model



PBR (Base case, 300days operation)			PBR (Base case, 360days operation)		
Technical parameters	**Unit**	**Value**	**Technical parameters**	**Unit**	**Value**
Biomass productivity	g/m2/day	20.00	Biomass productivity	g/m2/day	20.00
CO2 usage	kg/kg algae biomass	2.61	CO2 usage	kg/kg algae biom	2.61
Water evaporation	L/m2/day	0.50	Water evaporation	L/m2/day	0.50
Mixing power consumption	w/m2	500.00	Mixing power consumption	w/m2	500.00
Labour	people/ha	0.36	Labour	people/ha	0.36
Production days	Days	300.00	Production days	Days	360.00
Land area	ha	10.00	Land area	ha	10.00
Ratio V/S	m3/m2	0.07	Ratio V/S	m3/m2	0.07
CO2 fixation efficiency		0.69	CO2 fixation efficiency		0.69
Dilution rate	1/day	0.40	Dilution rate	1/day	0.40
Total culture volume	m3	7,000.00	Total culture volume	m3	7,000.00
Total biomass production	ton/ha/year	60.00	Total biomass production	ton/ha/year	72.00
Total CO2 consumption	ton/ha/year	156.60	Total CO2 consumption	ton/ha/year	187.92
Total water evaporation	ton/ha/year	1,500.00	Total water evaporation	ton/ha/year	1,800.00
Water cost	€/kg	0.05	Water cost	€/kg	0.05
CO2 cost	€/kg	0.10	CO2 cost	€/kg	0.10
Nutrients cost	€/kg	0.40	Nutrients cost	€/kg	0.40
Fertilizers usage	kg/kg algae biomass	0.30	Fertilizers usage	kg/kg algae biom	0.30
Power cost	€/kWh	0.05	Power cost	€/kWh	0.05
Power for harvesting and others	kWh/m3 harvest	1.00	Power for harvesting and others	kWh/m3 harvest	1.00
Photobioreactor cost	€/m3	2,000.00	Photobioreactor cost	€/m3	2,000.00
PBR (Porjected case, 300days operation)			**PBR (Projected case, 360days operation)**		
Technical parameters	**Unit**	**Value**	**Technical parameters**	**Unit**	**Value**
Biomass productivity	g/m2/day	40.00	Biomass productivity	g/m2/day	40.00
CO2 usage	kg/kg algae biomass	2.61	CO2 usage	kg/kg algae biom	2.61
Water evaporation	L/m2/day	0.50	Water evaporation	L/m2/day	0.50
Mixing power consumption	w/m2	50.00	Mixing power consumption	w/m2	50.00
Labour	people/ha	0.36	Labour	people/ha	0.36
Production days	Days	300.00	Production days	Days	360.00
Land area	ha	10.00	Land area	ha	10.00
Ratio V/S	m3/m2	0.07	Ratio V/S	m3/m2	0.07
CO2 fixation efficiency	0	0.69	CO2 fixation efficiency	0	0.69
Dilution rate	1/day	0.40	Dilution rate	1/day	0.40
Total culture volume	m3	7,000.00	Total culture volume	m3	7,000.00
Total biomass production	ton/ha/year	120.00	Total biomass production	ton/ha/year	144.00
Total CO2 consumption	ton/ha/year	313.20	Total CO2 consumption	ton/ha/year	375.84
Total water evaporation	ton/ha/year	1,500.00	Total water evaporation	ton/ha/year	1,800.00
Water cost	€/kg	-	Water cost	€/kg	-
CO2 cost	€/kg	-	CO2 cost	€/kg	-
Nutrients cost	€/kg	-	Nutrients cost	€/kg	-
Fertilizers usage	kg/kg algae biomass	0.30	Fertilizers usage	kg/kg algae biom	0.30
Power cost	€/kWh	0.05	Power cost	€/kWh	0.05
Power for harvesting and others	kWh/m3 harvest	1.00	Power for harvesting and others	kWh/m3 harvest	1.00
Photobioreactor cost	€/m3	2,000.00	Photobioreactor cost	€/m3	2,000.00